SD11
A574
#212

United States
Department of
Agriculture

Forest
Service

North Central
Research
Station

General Technical
Report **NC-212**

Integrated Tools for Natural Resources Inventories in the 21st Century

Proceedings of the IUFRO Conference
August 16-20, 1998
Boise, Idaho, USA

Mark Hansen and Thomas Burk, Editors

Conference Planning Committee:

Co-General Chair - Program:	Dr. Mark Hansen, USDA Forest Service
Co-General Chair - Logistics:	Dr. Steve Fairweather, Olympic Resource Mgt.
Tuesday Night Dinner:	Mr. Mike Wissenbach, Natural Resources Consulting
Vendors:	Dr. John Bell, John Bell & Associates, Inc.
Workshops:	Dr. Steve Prisley, Westvaco Corporation
Spouse/Guest Programs:	Ms. Calli Daly, Idaho Div. of Environmental Quality
Posters:	Dr. Chuck Stiff, Stiff Applied Technology, Inc.
Field Trips:	Dr. Dennis Mengel, Syringa Earth Resources

North Central Research Station
Forest Service—U.S. Department of Agriculture
1992 Folwell Avenue
St. Paul, Minnesota 55108
Manuscript approved for publication May 1, 2000
2000

Integrated Tools for Natural Resources Inventories in the 21st Century

Proceedings held at
Boise Centre on the Grove
Boise, Idaho

August 16-20, 1998

Edited by
Mark Hansen and Tom Burk

INTEGRATED TOOLS
FOR NATURAL RESOURCES
INVENTORIES IN THE 21st CENTURY

SPONSORS:

- Society of American Foresters
  - A1 (Forest Inventory) and A3 (Biometrics) Working Groups
  - Intermountain SAF
  - Southwest Idaho Chapter
- International Union of Forest Research Organizations (4.02)
- USDA Forest Service
- Boise Cascade Corporation
- Canadian Forest Service
- American Statistical Association
- American Forest & Paper Association
- Westvaco Corporation

ROCKY MOUNTAIN RESEARCH STATION LIBRARY
FORT COLLINS CENTER
240 W PROSPECT RD
FORT COLLINS, CO 80526-2098

The use of trade, firm, or corporation names in this publication is for the information and convenience of the reader. Such use does not constitute an official endorsement or approval by the U.S. Department of Agriculture or the Forest Service of any product or service to the exclusion of others that may be suitable. Statements of the contributors from outside the U.S. Department of Agriculture, Forest Service may not necessarily reflect the policy of the department.

PREFACE

Inventory has always been and continues to be central to forest management at all levels of practice. Designing, planning, and implementing inventories draws upon the expertise of many individuals within a forestry organization. For these reasons it is not surprising that our 1998 conference drew a contingent of over 325 forestry and related professionals from multiple organizational levels. There was also a distinct international flavor to the conference with over 30 foreign countries represented—again, evidence of the importance and pervasiveness of inventory in forestry practice.

By all accounts the gathering was a complete success: good attendance, a rich variety of papers, well-done presentations, fine hospitality and weather from the good folks of Boise, Idaho, and ample good food around which discussions could be continued and acquaintances made or reestablished. All this was made possible by the hard work of many people involved in organizing the conference and, of course, the enthusiastic participation of attendees.

Consideration of the papers presented at the conference points to several trends in inventory practice. The new "annual inventory" systems being developed were the subject of several papers, as well as a special session. Increased pressure on forest management has called for a corresponding increase in the need for timely data for which the annual inventory systems provide one approach. Concern over possible forest decline in many areas across the globe has spurred efforts in more effective forest health monitoring. These efforts continue to be improved in terms of statistical rigor and are now being seen as an integral component of a comprehensive inventory system. Growth modeling efforts and inventory have always been closely linked, but the use of models in the design of repeated inventories has grown considerably. Use of inventory data for model calibration and evaluation, as opposed to research plots, is receiving increased attention.

Remote sensing techniques continue to be evaluated for generating useful auxiliary data in forest inventories. Much has been learned with current efforts better matching imagery capability with data needs. Still greater gains will be needed as managers and decisionmakers call for more frequent inventories with broader applicability. Finally, a healthy call for simplicity in design was heard from many at the conference. Inventory data are being used to address an increasingly diverse set of questions by an increasingly diverse set of users. Optimality has little meaning under such circumstances, and statistical efficiency may not be conducive to broad application.

In addition to the conference paper and poster sessions, vendors shared the latest in technologies useful in inventories throughout the conference, and five half-day workshops presented the latest inventory tools. The conference ended with six field trips demonstrating a variety of current inventory techniques and implementations.

The papers that follow are generally "as provided" by the author. All authors were asked to obtain peer review of their manuscript, and we assume that was uniformly the case. Reviewers are identified in the acknowledgments of each paper. We have organized the papers into seven topical areas to give some sense of meeting themes.

Again, thanks to all those involved in organization and execution of this successful conference, especially to the members of the conference planning commitee—people who all put in lots of hard work and had great ideas—and to our sponsors who provided financial and other logistical assistance. We would also like to thank Lucy Burde and Mary Peterson for the hard work they did in editing and putting together these proceedings.

TABLE OF CONTENTS

Page

Design of Natural Resource Inventories

Multiresource Inventories Incorporating GIS, GPS, and Database Management Systems 1
Loukas G. Arvanitis, Balaji Ramachandran, Daniel P. Brackett, Hesham Abd-El Rasol, and Xuesong Du

History and Results of the Northern Forest Health Monitoring Program 8
Charles J. Barnett

Basic Truths for Planning and Executing an Inventory 14
John F. Bell

A Comparison of Sample Unit Designs in the National Inventory of the U.S. 20
B.E. Borders, G.H. Brister, N. Grahl, B.D. Shiver, and C.J. Ciezewski

Towards an Effective Integration of Forest Inventories and Natural Resources Surveys: The Italian Perspective 28
Piermaria Corona and Marco Marchetti

State-of-the-art Technologies of Forest Inventory and Monitoring in Raiwan 35
Fong-Long Feng

History of Forest Survey Sampling Designs in the United States 42
W.E. Frayer and George M. Furnival

Rebuilding Our Legacy Inventories: Identifying the Good and Fixing the Bad 50
Dave Gilbert, Keith Tudor, Sam Otukol, and Karen Jahraus

Pros and Cons of Continuous Forest Inventory: Customer Perspectives 60
Andrew J. R. Gillespie

Selection of Plot Remeasurement in an Annual Inventory 67
Mark H. Hansen, Hans T. Schreuder, and Dave Heinzen

Some Practical Aspects of Designing a Large Inventory 79
Dr. Kim Illes

Forest Resource Inventory Assessment in Gunung Rara Forest Reserve, Sabah, Using Stratified Field Sampling 86
Kamaruzaman Jusoff

A Comarison of Periodic Versus Permanent Surveys 94
Michael Köhl and Charles T. Scott

An Analysis of Mortality Inventory Tally Using Large Plots Compared to Tally Using Small Plot Clusters 104
Vernon J. LaBau and John W. Hazard

Some Aspects of Inventory Integration 110
Jerry Leech

Towards a Plot Size for Canada's National Forest Inventory 116
Steen Magnussen, P. Boudewyn, and M. Gillis

Overview of the Forest Health Monitoring Program 129
Robert D. Mangold

Page

A Prototype for Forest Health Monitoring in Indiana State Parks 141
Rachel Morse, KaDonna Randolph, and John W. Moser, Jr.

Setting Monitoring Objectives for Landscape-size Areas 145
Craig M. Olson and Dean Angelides

Boundary Plot Corrections for Variable Radius Plots—Simulation Results 148
Margaret Panner and Sam Otukol

Guided Transect Sampling—A New Design Combining Prior Information and Field Surveying 158
Anna Ringvall, Göran Ståhl, and Tomas Lämås

Pseudo-CFI for Industrial Forest Inventories 165
Francis A. Roesch

An Annualized Forest Inventory for Nebraska 171
Hans T. Schreuder and Tom D. Wardle

Effects of Different Definitions on Forest Area Estimation in National Forest Inventories in Europe 176
Berthold Traub, Michael Köl, Risto Päivinen, Olaf Kügler

Required Sample Size for Monitoring Stand Dynamics in Strict Forest Reserves: A Case Study 185
Diego Van Den Meersschaut, Bart De Cuyper, Kris Vanderkerkhove, and Noël Lust

Alternative Sampling Designs and Estimators for Annual Surveys 192
Paul C. Van Deusen

Analysis of Natural Resource Inventory Data 197
Uncertainty Estimation of the Self-Thinning Process by Maximum-Entropy Principle 199
Shoufan Fang and George Z. Gertner

Sources of Uncertainty in Annual Forest Inventory Estimates 207
Ronald E. McRoberts

Spatial Interpolation of Forest Conditions Using Co-Conditional Geostatistical Simulation 214
H. Todd Mowrer

A Miltivariate Decision Tree Analysis of Biophysical Factors in Tropical Forest Fire Occurrence 221
Rey S. Ofren and Edward Harvey

The Use of Multiple Imputation in the Southern Annual Forest Inventory System 228
Gregory A. Ream and Joseph M. McCollum

Estimating Two-Way Tables Based on Forest Surveys 234
Charles T. Scott

Spatial Terrain Analysis for Matching Native Tree Species to Sites: A Methodology 239
Robin N. Thwaites

Inventory Applications in the Management and Monitoring of Natural Resources 246
Can the Functional Stability of Forest Ecosystems be Evaluated from the Spatial Analysis of Stands?
A Case Study from the Bialowieza Primeval Forest (Poland) 248
Andrzej Bobiec

Page

Has Virginia Pine Declined? The Use of Forest Health Monitoring and Other Information in the Determination 258
William G. Burkman and William A. Bechtold

Forest Health Monitoring in California, Oregon, and Washington: Reseults and Interpretation 265
Richard T. Busing

FIA Forest Inventory Data for Wildlife Habitat Assessment 272
David C. Chojnacky

The Forest as a Warehouse 276
C. J. Goulding

Late-Successional Forsts and Northern Spotted Owls: How Effective is the Northwest Forest Plan? 283
Miles Hemstrom and Martin G. Raphael

Assessing Forest Fragmentation Metrics from Forest inventory Cluster Samples 292
Christoph Kleinn

Forest Cover Type, Habitat Diversity, and Anthropogenic Influences on Forest Ecosystems Adjoining the Masai Mara National Reserve, Kenya 296
James Legilisho-Kiyiapi

Integrated Permanent Plot and Aerial Monitoring for the Spruce Budworm Decision Support System 305
David A. MacLean

An Effectiveness Monitoring Program for the Northwest Forest Plan: New Approaches to Common Monitoring Problems 313
Craig Palmer, Barry Mulder, and Berry Noon

Evaluation of Habitat Suitability Index Models for Assessing Biotic Resources 321
John C. Rennie, Joseph D. Clark, and James M. Sweeney

Biological Diversity in the Sikhote-Alin Forests and Measures of its Conservation 326
V. A. Rosenberg, V. N. Bocharnikov, and S. M. Krasnopeev

Tracking the Health of Trees Over Time on Forest Health Monitoring Plots 334
Jim Steinman

Development of a Stand-scale Forest Biodiversity Index Based on the State Forest Inventory 340
Diego Van den Meersschaut and Kris Vanderkerkhove

Measurement Consistency in Natural Resources Inventories 351
Digital Terrestrial Photogrammetric Methods for Tree Stem Analysis 353
Neil A. Clark, Randolph H. Wynne, Daniel L. Schmoldt, and Matt Winn

Use of Three-Point Taper Systems in Timber Cruising 364
James W. Flewelling, Richard L. Ernst, and Lawrence M. Raynes

A Field Test of Cut-Off Importance Sampling for Bole Volume 372
Jeffrey H. Gove, Harry T. Valentine, and Michael J. Holmes

Reliability Assessment of Selected Indicators of Tree Health 377
Pawel M. Lech

Quality Control of Measurements Made on Fixed-Area Sample Plots 385
Ola Lindgren

Page

Modeling Variability and Scale Integration of LAI Measurements 392
Kris Nackaerts and Pol Coppin

Mathematical Form Models of Tree Trunks 399
Rudolfs Ozolins

Comparison of Optical Dendrometers for Prediction of Standing Tree Volume 407
Robert C. Parker and Thomas G. Matney

Development of the B.C. Vegetation Inventory Training Program 418
Norm Shaw

Using A Ceptometer to Validate A visual Evaluation of the Degree of Defoliation of Holm and Cork Oak Trees 425
Margarida Tomé and Maria Vasconcelos

Aboveground Biomass Equations for 7-year-old Acacia mangium Willd in Botucatu, Brazil 430
Ricardo A.A. Veiga, Maria A.M. Brasil, and Carlos M. Carvalho

Data Management and GIS in Natural Resource Inventories 435
Distributing Stand Inventory Data and Maps Over a Wide Area Network 437
Thomas E. Burk

DataPlustm—A Revolutionary Applications Generator for DOS Hand-Held Computers 444
David Dean and Linda Dean

Eucalyptus Forest Information System for the Portuguese Pulp and Paper Industry 453
Luis Fonseca, Rita Crespo, Henk Feith, José Luis Carvalho, António Macedo, and João Pedro Pina

Defining and Predicting Urban-Wildland Interface Zones Using a GIS-Based Model 457
Lawrence R. Gering, Angel V. Chun, and Steve Anderson

Using Sampling Theory as the Basis for a Conceptual Data Model 464
Fred C. Martin, Tonya Baggett, Tom Wolfe, and Roy Mita

Interfacing Natural Resource Inventories with Forest Growth Models 471
Growth and Yield Model Application in Tropical Rain Forest Management 473
James Atta-Boateng and John W. Moser, Jr.

Base-Age Invariance and Inventory Projections 481
C.J. Cieszewski, R.L. Bailey, B.E. Borders, G.H. Brister, and B.D. Shiver

A Review of Methods for Updating Forest Monitoring System Estimates 494
Hector Franco-Lopez, Alan R. Ek, and Andrew P. Robinson

Assessing Uncertainty in Mechanistic Models 501
Edwin J. Green, David W. MacFarlane, and Harry T. Valentine

The AFIS Tree Growth Model for Updating Annual Forest Inventories in Minnesota 507
Margaret R. Holdaway

Validation Databases for Simulation Models: Aboveground Biomass and Net Primary Productivity (NPP) Estimation Using Eastwide FIA Data 515
Jennifer C. Jenkins and Richard A. Birdsey

Calibration of the STEMS Diameter Growth Model Using FIA Data 525
Veronica C. Lessard

Page

A Survival Model for Individual Shortleaf Pine Trees in Even-Aged Natural Stands 533
Thomas B. Lynch, Michael M. Huebschmann, and Paul A. Murphy

Comparing the STEMS and AFIS Growth Models With Respect to the Uncertainty of Predictions 539
Ronald E. McRoberts, Margaret R. Holdaway, and Veronica C. Lessard

Utilizing Inventory Information to Calibrate a Landscape Simulation Model 549
Stephen R. Shifley, Frank R. Thompson III, David R. Larsen, David J. Mladenoff, and Eric Gustafson

Annual Updating of Plantation Inventory Estimates Using Hybrid Models 562
Peter Snowdon

Maximum Size-Density Relationships for Mixed-Hardwood Forest Stands in New England 570
Dale S. Solomon and Lianjun Zhang

Adaptation of FIBER for Forest Inventory and Analysis Growth Projections in the State of Maine 580
Dale S. Solomon, Thomas B. Brann, and Lawrence E. Caldwell

Inventory Implications of Using Sampling Variances in Estimation of Growth Model Coefficients 587
Albert R. Stage and William R. Wykoff

Evaluating a Model to Predict Timber Harvesting in Austria 596
Hubert Sterba, Michael Golser, and Klemens Schadauer

Remote Sensing Applications in Natural Resource Inventories 605
A New Sampling Scheme for Tropical Forest Monitoring Using Satellite Imagry 607
Frédéric Achard, Tim Richards, and Javier Gallego

Assessing Change in Large-Scale Forest Area by Visually Interpreting Landsat Images 614
Jerry Greer, Frederick P. Weber, and Raymond L. Czplewski

Change Detection Using NALC MSS Triplicates to Set Forest Planning Context 623
D.R. Grey, P.E. Gessler, M. Hoppus, and S.L. Boudreau

Ground-Based Photo Monitoring 631
Frederick C. Hall

Development of a Highly Automated System for the Remote Evaluation of Individual tree Parameters 638
Richard Pollock

Using Landsat Thermatic Mapper and SPOT Satellite Imagery to Inventory Wetland Plants of the Coeur d'Alene Floodplain 646
F.M. Roberts and P.E. Gessler

Data Fusion of Landsat TM and IRS Images in Forest Classification 654
Guangxing Wang, Markus Holopainen, and Eero Lukkarinen

A Comparison Between ERS-1, JERS-1, and Radarsat-1 Radar Satellite Imaging Systems and Landsat MSS & TM and Spot Optical Satellite Imaging System to Detect and Monitor Mangrove Deforestation in East Kalimantan, Indonesia 664
Mahfud M. Zuhair, Yousif Ali Hussin, and Michael Weir

Page

Special Purpose Inventories and Applications 669
Using Secondary Metabolites in the Monitoring of the Condition of Tree Stands Under Industrial Pollution 671
I.L. Fuksman

Integration of Ecological Indices in the Multivariate Evaluation of an Urban Inventory of Street Trees 673
J. Grabinsky, A. Aldama, A. Chacalo, and H.J. Vázquez

Modeling White-Tailed Deer Activity Patterns Across Forested Landscapes 680
Linda S. Gribko, Michael E. Hohn, and William M. Ford

Conservation and Restoration of Forested Wetlands: New Techniques and Perspectives 691
James Johnston, Steve Hartly, and Antonio Martucci

An Inventory of Multipurpose Avenue Trees of Urban Chandigarh, India 697
R.K. Kohli, H.P. Singh, and Daizy R. Batish

A Strategy for Monitoring Swiss Needle Cast and Assessing its Growth Impact in Douglas-fir Plantations of Coastal Oregon 705
Doug Maguire, Alan Kanaskie, and Mike McWilliams

The Urban Forest Effects (UFORE) Model: Quantifying Urban Forest Structure and Functions 714
David J. Nowak and Daniel E. Crane

Using Widely Spaced Observations of Land Use, Forest Atributes, and Intrusions to Map Resource Potential and Human Impact Probability 721
Victor A. Rudis

Adequacy of Different Experimental Designs for Eucalyptus Spacing Trials in Portuguese Environmental Conditions 734
Paula Soares and Margarida Tomé

The Effect of SO_2 Pollution on Pine Needle Structure 741
E.A. Zhitkova and L.L. Novitskaya

Design of Natural Resource Inventories

Multiresource Inventories Incorporating GIS, GPS, and Database Management Systems

Loukas G. Arvanitis, Balaji Ramachandran, Daniel P. Brackett, Hesham Abd-El Rasol and Xuesong Du

Abstract.—Large-scale natural resource inventories generate enormous data sets. Their effective handling requires a sophisticated database management system. Such a system must be robust enough to efficiently store large amounts of data and flexible enough to allow users to manipulate a wide variety of information. In a pilot project, related to a multiresource inventory of the Suwannee River Water Management District (SRWMD) holdings in Florida, a new temporal database model will be implemented. This model is a relational one with an enhanced entity relationship between component tables. It consists of a superclass, the spatial database index, and a number of subclass component tables related through a unique identifier. This superclass may be thought of as a central repository, where all the sample locations with their rectangular coordinates are stored. In addition, a unique identifier denoting various aspects of the sampling designs is associated with the coordinates. The global positioning system (GPS) will be used to reference sample locations for periodic updates. The model will be implemented via Oracle's database server. ArcView's Event Theme option will be used to integrate the processed data with existing spatial data sets for further analysis. This approach will have the advantage of working with smaller sets of data as opposed to the traditional geographic information systems (GIS) spatial analysis. The ultimate objective is to provide timely and reliable information for making intelligent decisions.

The State of Florida is divided into five water management districts. As state agencies, the didtricts' mission is to protect streams, freshwater springs, lakes, wetlands, underground water supplies, forests, wildlife, biodiversity, and other natural resources within each district for the benefit of the public. Intelligent management and conservation of these often fragile resources require a multitude of reliable multiresource data in a timely and cost-effective manner. For the past few months, we have been working with the Suwannee River Water Management District in designing an inventory system that will provide the information needed for future planning. The district currently owns and protects close to 100,000 acres (40.5 thousand ha) of river frontage and wetlands, just over 2 percent of the total land area of 4.9 million acres (1.98 million ha) located within its boundaries.

The district has an aggressive program of buying sensitive lands to secure future supply of water while protecting other valuable natural resources in its jurisdiction. Our task is limited to forest and vegetation sampling. However, the database that was developed provides also for wildlife; rare plants; shrubs; recreational, cultural, and geological features; water structures; access points trails; conservation areas; and many other details of the landscape profile and its various ecosystems. A number of powerful tools will be used in conducting this project: GIS, Relational Database Management System, GPS, and Spatial Statistics.

LITERATURE REVIEW

Geographical Information System

GIS has come a long way from the initial simple cartographic tool for automated map production and display. It is viewed now as a powerful component of information systems for spatial analysis of complex knowledge-based systems. Such systems have embraced the spatial component that GIS brings to various organizations. It is an integral part of decisionmaking in various fields ranging from natural resources, environment, and utilities to mining, planning, and many others. As Berry (1995) puts in his article, "Ask not what you can do for GIS, but what GIS can do for you." The potential of GIS is being realized in every field, and its acceptance is increasing.

Professor, School of Forest Resources and Conservation, University of Florida, Gainesville, FL, USA; Research Assistant, Department of Civil Engineering, University of Florida, Gainesville, FL, USA; GIS Programmer/Analyst, School of Forest Resources and Conservation, University of Florida, Gainesville, FL, USA; Visiting Scientist, Department of Geology, Suez Canal University, Ismailia, Egypt; and Graduate Assistant, Department of Computer Information Systems, University of Florida, Gainesville, FL, USA, respectively.

Before too long, even ordinary persons will use some type of GIS without realizing it as such.

The major challenge facing GIS users is to integrate it effectively with decisionmaking algorithms as well as with numerous existing and emerging technologies, such as external relational database management systems (RDBMS), GPS, and Remote Sensing Imagery. In our case, focus is on the integration of RDBMS to handle descriptive data, GPS to georeference the locations of interest, and geostatistics to model spatial relationship in a multiuser environment (fig. 1).

In a good GIS, about 80 percent of the resources are related to database development and management. The spatial data sets become rather static once created. The frequency of updates is considerably low compared to that of descriptive data. In most multiresource inventories, descriptive data are more dynamic than spatial data. A good GIS design is one that incorporates a powerful database management system for efficient data storage and fast retrieval and manipulation of data.

Relational Database Management System

Database management systems have progressed from simple flat files to hierarchical, network, relational, and object-oriented systems. The most popular and powerful one is the relational database management system. It is based on a simple high-level language, known as Structured Query Language (SQL). A relational model represents the data in a database as a collection of relations. Each relation can be thought of as a table of values. Each row in the table represents a collection of related data values. These values can be interpreted as a fact describing an entity or a relationship instance (Elmasri and Navathe 1989).

Object-oriented database management systems are promising, especially in handling spatial data. However, they require a high-level language such as C++, SmallTalk, or JAVA. Some of the major advantages in using RDBMS, as opposed to the tabular management module that comes with traditional GIS software, are the following:

Data redundancy.—Often in multiresource inventories, large amounts of redundant data are collected. For example, foresters collect data on tree species, diameters, heights, site quality, health, regeneration, groundcover, and others. Similar data may also be collected by ecologists in the same spatial domain. This can be avoided by storing relevant information as individual tables in a central RDBMS and retrieving what is needed for specific studies in a cost-effective manner.

Performance Efficiency.—Studies have been conducted to evaluate the query and update efficiency by linking GIS with an external RDBMS (Sawicki 1995, Hejazi

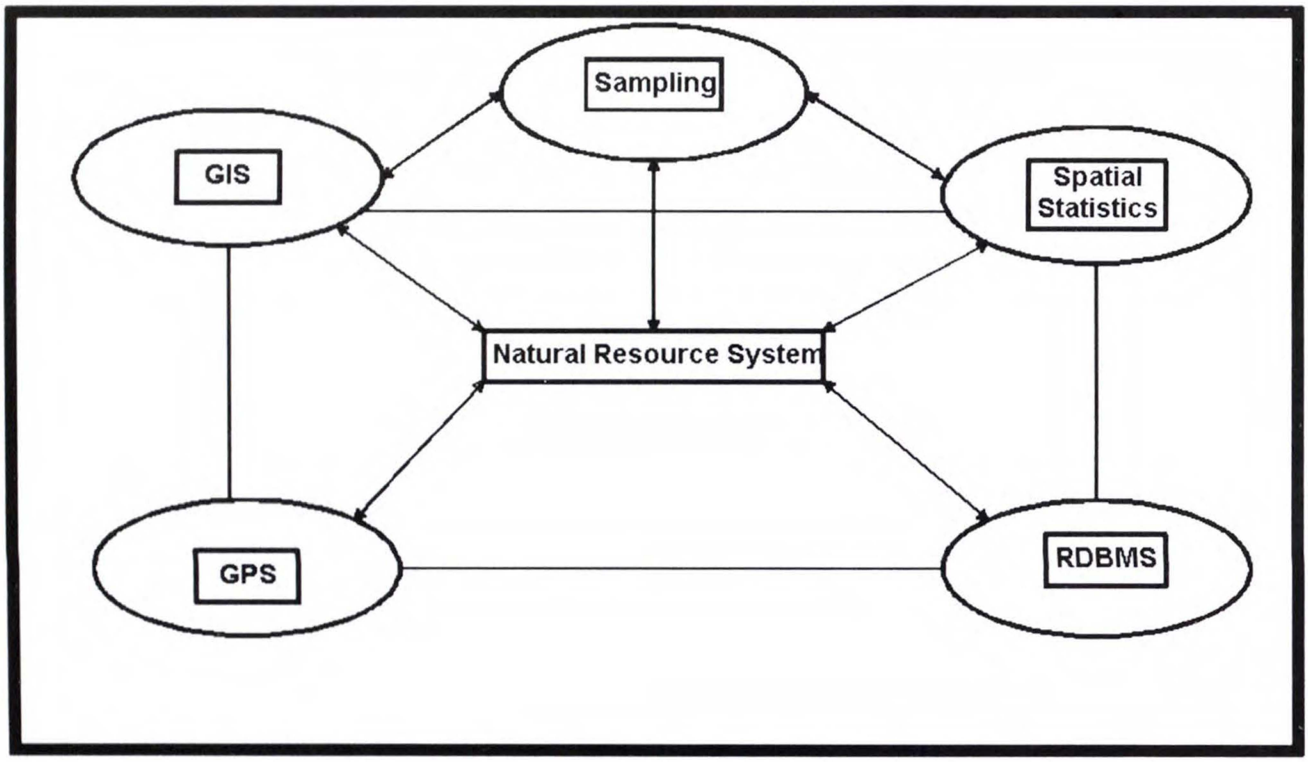


Figure 1.—*Components of a natural resource inventory pilot study for the Suwannee River Water Management District.*

1997, Guan 1997). In these studies, the authors have used external RDBMS as a substitute for the tabular management module in existing GIS software. It has been shown that the database could be managed about 95 percent more efficiently for data entry, update, and querying when stored in an external database (Hejazi 1997). Our model is unique in the sense that the data exchange is bi-directional.

Data Integrity.—SQL allows users to develop databases by employing integrity rules. For example, if one is maintaining an employee database, the Social Security Number (SSN) is a unique value that represents a specific person. SQL will not allow users to enter two records with the same SSN. Similarly, domain constraints, table constraints, column constraints, row constraints, check constraints, system constraints etc., to name but a few, could be applied accordingly to prevent corruption of good data by transcription errors and/or negligence of end users who are populating the database. This kind of rules and constraints also contributes to efficient database administration.

Multiuser environment.—The biggest asset of RDBMS in a network environment is to provide multiuser accessing capabilities. Users can update or retrieve data from the same table simultaneously. RDBMS provide concurrency control mechanisms to handle multiuser transactions. Any organization will benefit by sharing the same information from a single source. This reduces the overhead associated with maintaining databases at each terminal.

Security.—This feature allows selective access to various parts of a database. Some users may be allowed to access certain tables of the database for input only, but may not have update and/or delete privileges. Depending on a user's needs and the organizational hierarchy, individual user authorization profiles can be created. This prevents users from performing operations that corrupt or destroy the data.

Database Backup and Recovery.—Usually, backup refers to copying the whole database on to a disk once a week or at the end of the day, depending on the frequency of transactions. Any failure between these backup periods results in loss of data. With RDBMS, the database can be recreated from the start to the last completed transaction without loss of data.

Client-Server Architecture.—This model allows clients and servers to be placed independently on nodes in a network. It provides the opportunity for cross platform access to the database through PC, NT, or Mac computers over the network.

Cost-effective Application Development.—Since database is based on SQL with integrity rules, the time required to develop new applications is reduced considerably, to about one-sixth of the effort required to develop traditional file system applications (Elmasri and Navathe 1989).

Global Positioning System

The Navstar Global Positioning System (Navstar GPS) was employed in the late sixties by the US Department of Defense (DoD) for strategic military navigation. The system provides accurate, continuous, worldwide, three-dimensional position and velocity information to users (Kaplan 1996). The GPS has three main sectors: space segment, control segment, and user segment. The space segment consists of a constellation of 24 satellites, including three backup satellites, orbiting the earth at high altitudes (around 20,200 km). The control segment is the heart of the GPS system and monitors the space segments. It is operated by DoD from Falcon Air Force Base, Colorado Springs, CO, USA. This control segment monitors the satellites' transmission of navigation messages and sends adjustments, if required. The third component is the user segment where several applications use GPS signals for mapping, navigational, and other tasks. Some of the civilian GPS applications are in the area of agriculture, such as precision farming, transportation for aviation and vehicle tracking, emergency response services, forestry, wildlife, and other natural resource studies. It is estimated that the civilian users outnumber those of the military (Trimble 1998).

In terms of accuracy, GPS can be broadly classified into three categories: survey, mapping, and recreational. The sources of error in GPS signal are selective availability (S/A), obstruction, multipath, and atmospheric delay. The major error component is S/A, which is controlled by DoD to prevent hostile forces from using GPS for malicious purposes.

In 1992, the USDA Forest Service GPS Steering Committee identified more than 130 possible forest applications (Kruczynski and Jasumback 1993). These include area estimation for timber sales, inventories, archaeological sites, red-cockaded woodpecker sites, genetically superior trees, delineation of forest stands, location and navigation to permanent plot points, roads and trails, fire perimeter mapping, wildlife monitoring using GPS based telemetry system, water sources and structures, as well as property corners (Rodgers *et al.* 1996, Evans *et al.* 1992). The biggest obstacle in the implementation of GPS in forestry is canopy interference and mulitpathing of signals. Studies have been conducted under variable forest canopies, terrain, and satellite availability to evaluate GPS accuracies (Deckert and Bolstad 1996). The results from these indicate a postprocessed accuracy ranging from 3 to

6 m, the latter under the worst conditions. Ongoing navigational studies at the Austin Cary Memorial Forest, School of Forest Resources and Conservation, University of Florida, have resulted in a submeter accuracy when navigating to sample points (Brackett. D, personal communication 1998). This can be attributed to the relatively flat terrain, close proximity to Coast Guard real-time differential correction signals, canopy structure, and good mission planning.

METHODOLOGY

Sampling Design.—The elementary sampling unit is a cluster of four circular subplots, recently adopted by the Southern Research Station of the USDA Forest Service (fig. 2). The radius of each subplot is 24 ft (7.32 m), and the distance between subplots is 120 ft (36.6 m). Around the center of each sublot, a microplot of 6.8 ft (2.07 m) in radius will be established. All trees of 5.0 in. (12.7 cm) or larger dbh within each subplot will be measured. In each microplot, all live trees between 1.0 and 4.9 in. (2.54 and 12.69 cm) in dbh, as well as the four dominant seedlings will also be measured.

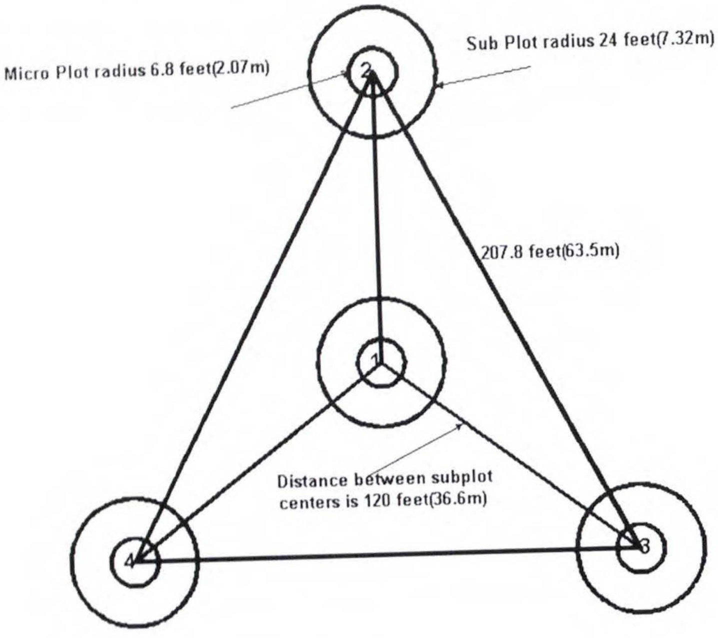

Micro Plot radius 6.8 feet(2.07m)
Sub Plot radius 24 feet(7.32m)
2
207.8 feet(63.5m)
1
Distance between subplot centers is 120 feet(36.6m)
4
3

Figure 2.—*Plot configuration.*

Individual clusters will be located systematically along transect lines. To minimize the adverse effects of periodic variation, the center of each cluster will be located along a random azimuth with a differentially corrected GPS receiver at a fixed distance from the transect line (fig. 3). This approach will also facilitate subsequent spatial predictions (kriging). The estimated from pre-sampling average basal area per acre for all trees larger than 5.0 inches dbh and its corresponding variance will be used to compute the required sample size, assuming a 0.95 confidence coefficient and an allowable error of estimate ±0.10 of the mean. These were the requirements set by the SRWMD, following numerous discussions. Obviously, the precision of the rest of the many variables of interest will vary considerably.

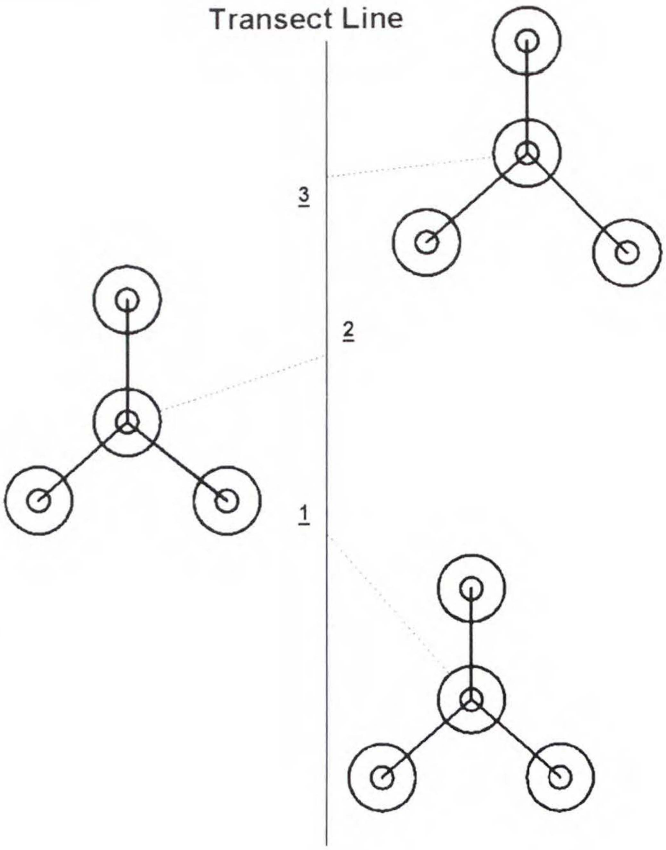


Figure 3.—*Allocation of clusters.*

Percent ground cover by vegetation and its species composition will be estimated from four 50- x 50-cm quadrats located systematically on a random strip, 50 cm wide and 2.07 m long, through the center of the four microplots of each cluster (fig. 4).

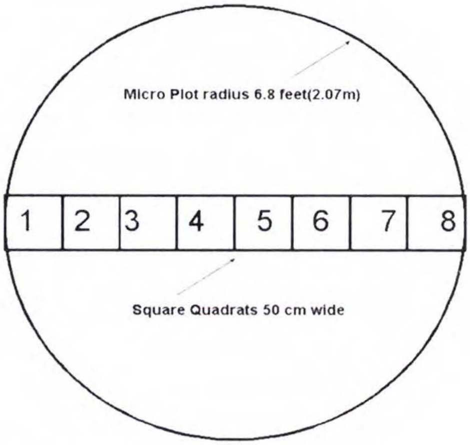


Figure 4.—*Ground cover sampling design.*

System Implementation.—The architecture of the database model is depicted by figure 5. On the server side, Oracle

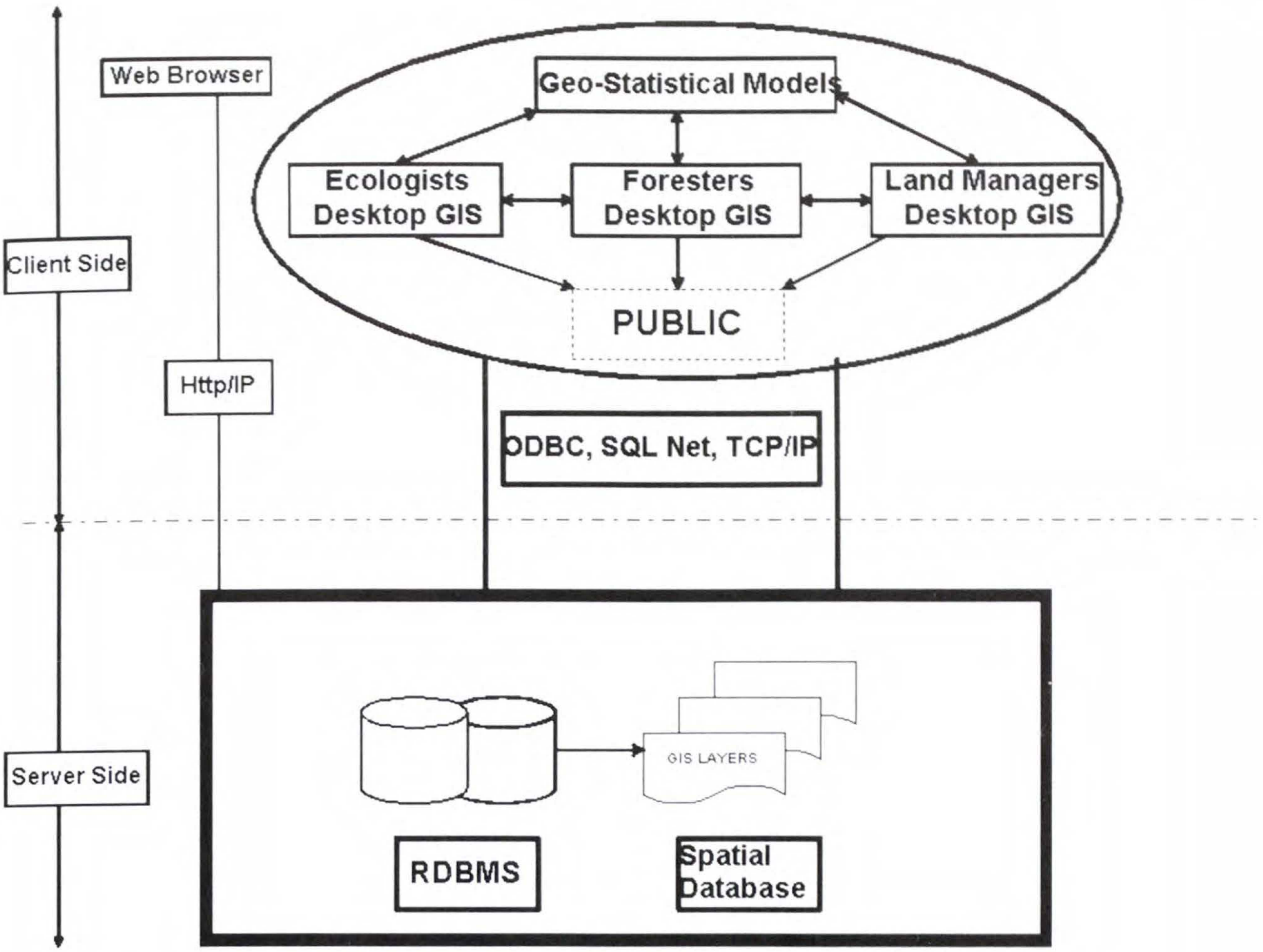


Figure 5.—*Natural resource inventory: System implementation.*

Corporation's *Oracle7* workgroup server for SPARC Solaris and the Environmental Systems Research Institute (ESRI) *Arc/Info* Librarian are used. On the client side, ESRI's desktop GIS, *ArcView* version 3.0a, and corresponding applicable models will be installed in a PC network environment.

The client, the *ArcView* application in this case, is allowed to access data in an *Oracle7* database through the Open Database Connectivity (ODBC) interface. ODBC basically consists of a driver manager and a set of ODBC drivers that enable applications to access data using SQL as a standard language. It communicates with the network through *SQL*Net*, which is an Oracle product that works with the Oracle server and enables two or more computers that run the Oracle server to exchange data through a third-party network. *SQL*Net* is independent of the communications protocol, such as TCP/IP or Microsoft LAN Manager. Users can interface it with many network environments. Similarly, the centralized database can be accessed using web browsers through the Internet protocol.

In this multiresource inventory, a wide variety of entities need to be captured. It is a real challenge to develop a database that incorporates diverse entity types ranging from static features like water structures and access points to highly dynamic natural resource data. The proposed temporal database model is a relational one with enhanced entity relationships between component tables (fig. 6). It consists of a superclass, called spatial database index, and a number of subclass component tables related through a unique identifier. The superclass may be thought of as a central repository, storing all the sample locations with their rectangular coordinates for entities associated with sampling. Entities that are linear or area features like trails or water structures will have only a unique identifier without coordinates. This unique identifier will be later used to join with its GIS coverage identifier for analysis. The spatial database index serves as a link between the spatial domain and the descriptive data associated with the domain. A field name 'Type' will be added to this table, which keeps track of the entity type like wildlife, rare-plant component, water structures, and others.

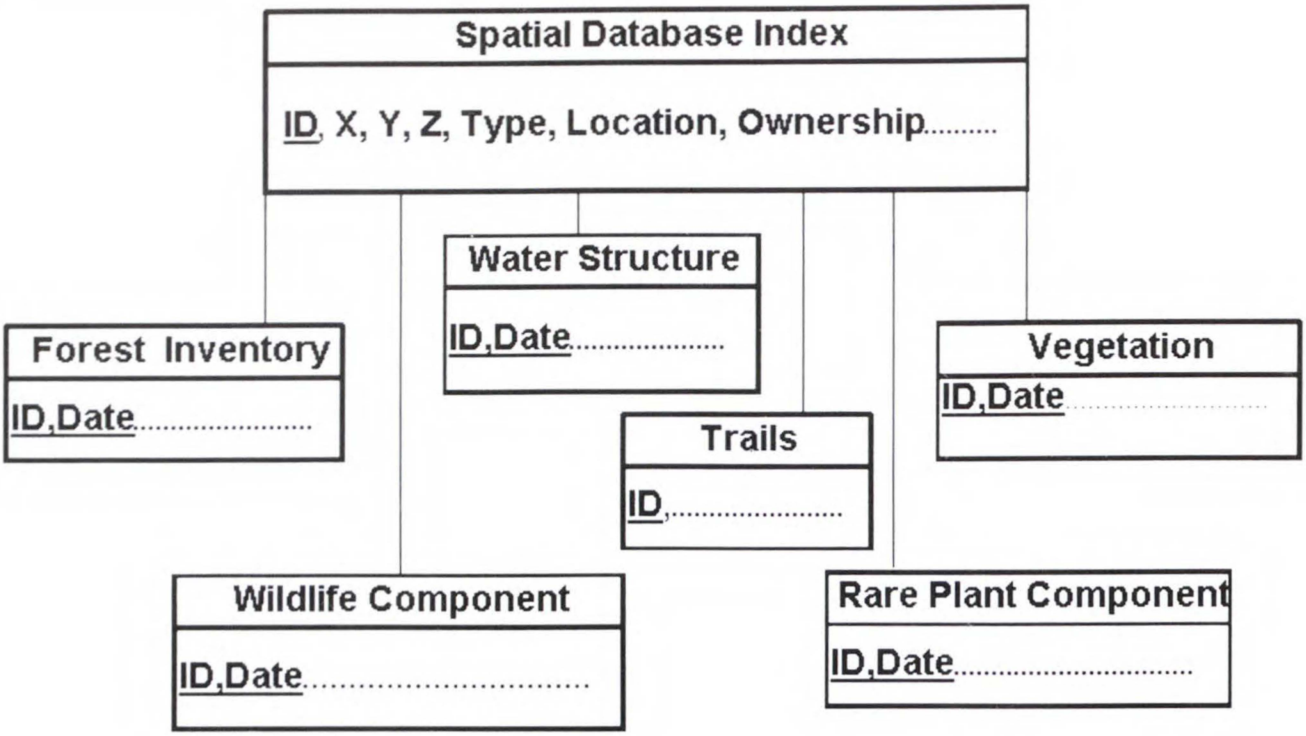

Spatial Database Index
ID, X, Y, Z, Type, Location, Ownership.........
Water Structure
ID,Date...................
Forest Inventory
ID,Date......................
Vegetation
ID,Date..........................
Trails
ID,.......................
Wildlife Component
ID,Date..............................
Rare Plant Component
ID,Date..............................

Figure 6.—*Partial entitiy relationship diagram showing the database structure.*

The temporal nature of the database is implemented by adding a date attribute as a primary key in the required subclass component tables. Thus, the inventory-related entities associated with sample points will be revisited using GPS for periodic updates. As an example, each individual tree with a diameter greater than 10 cm at breast height is stored for trend analysis and modeling. In this phase of the project, the temporality of the database consists entirely of snapshots. Any changes that occur between two time snapshots, if inferred through satellite imagery, aerial photography, or other means, will be properly accounted for in the models. Attempts are being made to model this database to make it truly temporal in the future.

Once the appropriate number of sample clusters is determined, a systematic grid will be superimposed on the pilot study area using *ArcInfo*. A program is written to generate sample clusters, which will be systematically located along transect lines at random azimuth and constant distance from transects. The coordinates of the center of each cluster will be used to monument the plot centers using GPS. Later, the coordinates will be stored as waypoints in the GPS units for field personnel to navigate to the cluster center. Other entities like water structures, access points, and archaeological features will also be georeferenced with GPS.

The final phase of this project will be to integrate processed data from the database with various spatial statistical models and for spatial analysis in *ArcView*. There are many options for accessing the database.

Novice users can employ the customized *ArcView* application, which uses SQL connect option to activate pre-compiled stored procedures and SQL scripts in the Oracle database. This would allow users to perform predefined summaries, reports, and other spatial analysis functions.

Users with advanced knowledge will be given the option of changing parameters to fit their own analysis objectives. For example, an ecologist may query the main spatial database index table in the field 'Type' just for wildlife and ground cover. With *ArcView's* event theme option, the resultant table from the query may be added to a point theme for further analysis with the existing spatial datasets like soils, hydrology, topography, roads, and others. Subsequently, foresters may debate on the use of a management action, such as prescribed burn, and assess its anticipated impact on wildlife in the area of interest. Similarly, the user can bring the whole Spatial Database Index table as a theme and drag a bounding rectangle or select a polygon from the existing base themes to obtain the points falling within his/her selection. Based on the selection, other information could be retrieved for those points from the Oracle database. The same methodology applies while running the models; they could be run either for the whole area or just for the data falling within oneís area of interest.

There is a concern about integrating highly accurate GPS information with existing GIS coverages that vary in accuracy. In this project, most of the coverages are generated from digital orthoquads (1-m resolution) with accuracy comparable to the one obtained by GPS in forested areas. In cases where it is required to use data from other sources the different accuracies will be dealt properly in the models and reporting results from such an analysis.

In summary, all indications suggest that future forest and other natural resource inventories will increasingly employ some type of a relational database. In addition, use of existing and emerging new technologies, including high-resolution remote sensing imagery, will continue to play an important role in providing timely, reliable, and cost-effective information for policy formulation and intelligent decisionmaking.

ACKNOWLEDGEMENTS

We gratefully acknowledge the cooperation of Charles H. Houder , III, and Robert Heeke of the Suwannee River Water Management District, Live Oak, FL, USA.

LITERATURE CITED

Berry, J.K. 1995. Spatial reasoning for effective GIS; with a collection of mathematical formulae by Nigel Waters. Fort Collins, CO: GIS World Books. 208 p.

Deckert. C.J.; Bolstad, P.V. 1996. Global positioning system(GPS) accuracies in eastern U.S. deciduous and conifer forests. Southern Journal of Applied Forestry. 20(2): 81-84.

Elmasri, R.; Navathe, S.B. 1989. Fundamentals of database systems. Redwood City, CA: The Benjamin/ Cummings Publishing Company, Inc. 802 p.

Evans, D.L.; Carraway, R.W.; Simmons, G.T. 1992. Use of global positioning system (GPS) for forest plot location. Southern Journal of Applied Forestry. 16(2): 67-70.

Guan, W. 1997. Evaluating ARC-to-Oracle linkages. Geo Info Systems. 7(2): 38-44.

Hejazi, F. 1997. Implementation of ORACLE in an ARC/ INFO-ARCVIEW GIS environment. In: ESRI's user conference proceedings; 1997 July 8-11; Redlands, CA. Environmental Systems Research Institute Inc. http://www.esri.com/library/userconf/proc97/ prochome.html

Kaplan, E.D. 1996. Understanding GPS principles and applications, mobile communication series. Boston, MA: Artech House, Inc. 554 p.

Kruczynski, L.R.; Jasumback, A. 1993. Forestry management applications, Forest Service experiences with GPS. Journal of Forestry. 91(8): 20-22.

Rodgers, A.R.; Rempel, R.S.; Abraham, K.F. 1996. A GPS-based telemetry system. Wildlife Society Bulletin. 24(3): 559-566.

Sawicki, J. 1995. ARC/INFO and ORACLE: an approach for feature storage and representation from oracle. In: ESRI's user conference proceedings; 1995 May 22-25; Redlands, CA. Environmental Systems Research Institute, Inc. http://www.esri.com/library/ userconf/proc95/prochome.html

Trimble. 1998. Surveying and mapping product training, ProXR/XRS with pathfinder office classroom manual. Sunnyvale, CA: Trimble Navigation Limited. 210 p.

History and Results of the Northern Forest Health Monitoring Program

Charles J. Barnett

Abstract.—The Forest Health Monitoring (FHM) Program was established because of a concern that the forests in the United States were declining. The program was established to monitor the state of and changes in forest conditions across the nation. This report looks at the distributions of trees into various rating categories for three variables collected on the FHM plots from 1991 through 1997. Based on these distributions, some year to year fluctuations are seen in the samples, attributed mostly to changes in the sample composition. Future analyses will need to control these differences in sample composition and will need to look at trends across the same set of trees.

The forests of New England have undergone many changes. At the time of European settlement, the regi was largely forested. The land was cleared for agricu but has been reverting back to forests since the 1800's cities continue to expand, the forests are being divide into smaller acreages among more people. The effect natural stressors (severe weather, insects, and disease also influencing forest structure, functions, and proce The effects of non-natural stressors (atmospheric dep tion and pollution, and global warming) on the region forests are the most recent phenomena to cause conce about the health of these forests.

To respond to the concerns about the natural environn raised by people in New England and elsewhere, the United States Congress directed the USDA Forest Ser to design a program to monitor the status (or "health", the nation's forests. The Forest Ecosystems and Atmospheric Pollution Act of 1998 (Public Law 100-521) directs the Forest Service to "...conduct such surveys as are necessary to monitor long-term trends in the health and productivity of domestic forest ecosystems."

The Forest Service monitors forest growth and productivity through its periodic forest surveys. To monitor trends in the health of forests, a new system of activities was established. In cooperation with state forestry agencies, and the U.S. Environmental Protection Agency (USEPA), the Forest Service initiated the Forest Health Monitoring (FHM) program in 1990 by establishing a plot network in six New England states (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, and Vermont).

Since 1990, the national FHM program has grown to include 27 states divided among four regional programs (fig. 1). As of 1998, the Northern FHM program has 16 states. By the end of 1999, the program will be operating in 18 states (fig. 2). Eventually, the Northern program will collect forest health data in 24 states in the northeastern and north-central United States. All four regional programs coordinate activities with a central, national office to implement the FHM program.

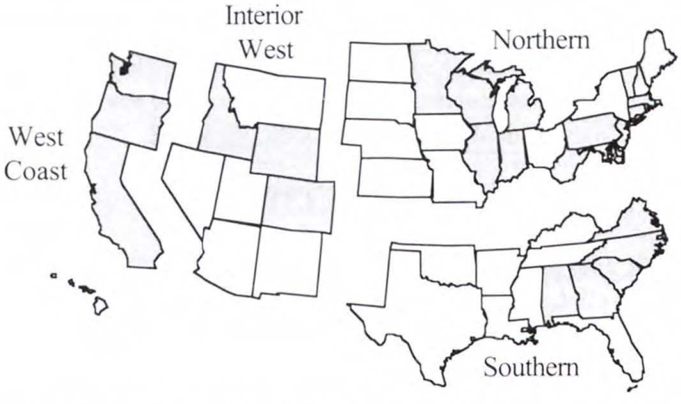


Figure 1.—*The four regional divisions of the national Forest Health Monitoring (FHM) program. States included in the 1998 FHM program are shaded in gray.*

The state agencies and universities that participate in the Northern FHM program are key to its success. They provide the field crews for data collection, both on and off the plots. In addition, they provide input used in the improvement of the program's measurements. Finally, they provide support and direction, particularly through the National Association of State Foresters (NASF), so that the program is able to keep expanding into new states.

The FHM program is designed to be a "...systematic assessment of the state and change in forest health." It is systematic in that the plots are established on a grid with periodic remeasurements. FHM aerial and ground surveys include the plot locations. The program is an assessment of various indicators of forest health. The

---

Acting Program Coordinator, Northeastern Research Station, USDA Forest Service, Radnor, PA, USA.

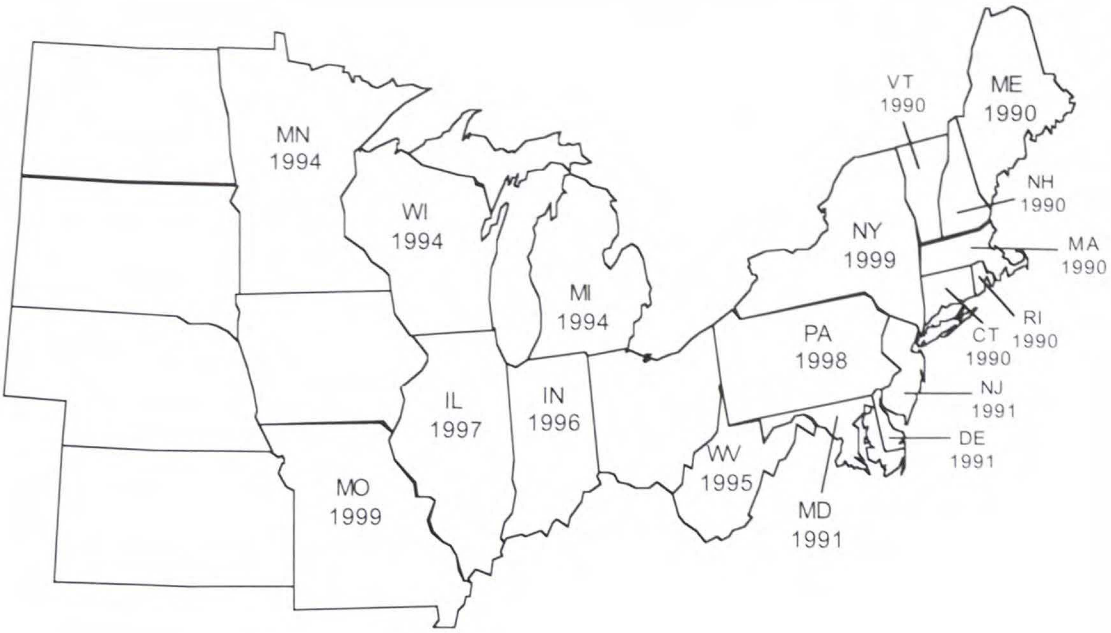


Figure 2.—*The states included, or to be included, in the Northern Forest Health Monitoring program and the year of entry into the program.*

results of these assessments are reported annually. The program reports on the state and change of forest health, looking at current conditions and changes in those conditions over time. Finally, forest health is assessed with measurements in various indicator sets, including: growth and yield, visual crown symptoms, species diversity and composition, insect and disease status, ozone bioindicator plants, and biogeochemistry.

As can be seen, the FHM program collects a large amount of information on forest health. This paper presents a summary of differences between years in the state of three crown condition variables (crown dieback, foliage transparency, and crown density) collected on overstory trees on the Northern FHM plots.

METHODS

The FHM data were collected according to national FHM data collection standards (USDA Forest Service 1998). Even though the FHM program was begun in 1990, significant changes were made to some of the protocols in 1991. Since 1991, the methods for the collection of the crown condition data have remained consistent. Table 1 shows the number of live trees greater than 5.0 inches diameter at breast height (dbh) on which data were collected for the years 1991 through 1997. The data for Pennsylvania are from plots established in 1995 as part of a separate regional study. These plots were approximately one-fourth of the total number of plots established in 1998, when Pennsylvania officially joined the program.

Table 1.—*Number of live trees, 5.0 inches dbh and greater, by year and species group*

Year	Hardwoods	Softwoods
	Number	*Number*
New England		
1991	2,602	1,754
1992	2,535	1,684
1993	3,230	2,618
1994	3,171	2,526
1995	3,375	2,645
1996	1,197	847
1997	1,006	992
Mid-Atlantic		
1991	351	126
1992	334	117
1993	553	166
1994	541	158
1995	2,257	203
1996	1,293	103
1997	1,435	112
Lake States		
1991	—	—
1992	—	—
1993	—	—
1994	5,719	2,640
1995	4,970	2,560
1996	3,140	1,312
1997	2,519	1,183

It should be noted here that the numbers of plots and trees measured in each state vary from year to year. For the years 1991 through 1995, all trees on all forested plots were evaluated every year. Beginning in 1996, the FHM program began measuring plots on a 4-year cycle, with approximately one-third of the total number of plots evaluated each year. (Each year's sample of plots is made up of one-fourth of the total plots plus an overlap set of plots measured to estimate year to year variability.) The numbers of trees change from year to year due to tree mortality or removal, ingrowth, changes in the use of the land containing an FHM plot, different plots being measured each year, or crews not being able to evaluate the trees because of conditions on the plot.

The variables analyzed for differences are crown dieback, foliage transparency, and crown density. Measurements for each variable are made for each tree. The measurements are estimated into five percent rating classes ranging from 0 to 100 percent. These ratings are based on the estimated percentage of the tree's crown that meets the definition of the variable. The variables are defined as follows:

Crown Dieback—Recent mortality of branches with fine twigs, which begins at the terminal portion of a branch and proceeds toward the trunk. The lower the rating, the lower the mortality and presumably the healthier the tree.

Foliage Transparency—The amount of background (skylight, foliage of other trees) visible through the live, normally foliated portion of the crown or branch. The lower the rating, the thicker the foliage and presumably the healthier the tree.

Crown Density—The amount of crown branches, foliage, and reproductive structures that blocks light visibility through the crown. The higher the rating, the denser, and presumably healthier, the tree.

The states in the Northern FHM program are grouped into three subregional sets, as defined below.

New England	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont;
Mid-Atlantic	Delaware, Maryland, New Jersey, Pennsylvania, West Virginia;
Lake States	Illinois, Indiana, Michigan, Minnesota, Wisconsin.

The years for which data were available and used in these analyses for each state are as follows:

1991-1997:	Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont, Delaware, Maryland, New Jersey
1994-1997:	Michigan, Minnesota, Wisconsin
1995-1997:	West Virginia
1996-1997:	Indiana
1995 only:	Pennsylvania
1997 only:	Illinois

The data were summarized by species group (hardwoods and softwoods) within each subregion. The results are presented in tables 2-4.

RESULTS AND DISCUSSION

Crown Dieback

For reporting the distribution of the dieback ratings, ratings are grouped into one of four categories. None contains those trees with dieback ratings of 0 to 5 percent; Light includes ratings from 6 to 20 percent; Moderate includes ratings from 21 to 50 percent; and Severe includes any ratings over 50 percent.

More than 95 percent of all trees in the samples in all subregions had no more than 20 percent crown dieback. The samples in the mid-Atlantic states showed a shift between 1995 and 1996. In the 1996 sample, the percentage of trees in the None category (0 to 5 percent dieback) decreased for both hardwoods and softwoods. There was a corresponding increase in the percentage of trees in the Light category. This shift is probably a result of Pennsylvania plots not being included in the 1996 sample, which allowed the West Virginia trees to have a greater influence on the sample for the Mid-Atlantic subregions. In 1996, there were reports of the effects of the beech bark disease complex on American beech (*Fagus grandifolia*, Ehrh.). For softwoods, there were increases in all three of the Light, Moderate, and Severe categories. The increase in the percentage of trees in the Light category absorbed most of the decrease in percentages in the None category.

In the Lake States subregion, the percentage of hardwoods and softwoods in the None category has decreased in each sample since 1994. This has been associated with a generally corresponding increase in the percentage of trees in the Light category. However, the combined total of percentages in the Moderate and Severe categories has remained relatively consistent, fluctuating between 2 and 3.5 percent for hardwoods and remaining at around 2.5

Table 2.—*Percentage distribution of live trees, 5.0 inches dbh and greater into four crown dieback classes by year and species group*

	Hardwoods				Softwoods			
Year	None (0-5%)	Light (6-20%)	Moderate (21-50%)	Severe (51+%)	None (0-5%)	Light (6-20%)	Moderate (21-50%)	Severe (51+%)
	Percent				Percent			
New England								
1991	78.4	17.3	2.9	1.4	93.3	5.5	0.6	0.6
1992	77.8	18.5	2.6	1.1	93.8	5.0	0.9	0.3
1993	69.7	26.2	3.1	1.0	88.5	8.8	1.3	1.4
1994	75.7	19.3	3.6	1.4	89.2	9.1	1.2	0.5
1995	76.4	19.4	2.9	1.3	89.1	9.1	1.3	0.5
1996	74.5	22.1	2.6	0.8	88.7	9.6	1.3	0.5
1997	77.8	19.1	2.4	0.7	92.3	6.3	1.1	0.3
Mid-Atlantic								
1991	70.1	29.3	0.6	0.0	78.6	20.6	0.8	0.0
1992	83.5	14.7	1.5	0.3	96.6	3.4	0.0	0.0
1993	91.1	8.0	0.7	0.2	95.8	3.6	0.6	0.0
1994	92.6	6.3	0.9	0.2	97.5	2.5	0.0	0.0
1995	91.8	6.3	1.1	0.9	97.0	3.0	0.0	0.0
1996	88.8	9.5	1.2	0.5	77.7	19.4	1.9	1.0
1997	91.6	7.5	0.5	0.4	84.8	15.2	0.0	0.0
Lake States								
1991	—	—	—	—	—	—	—	—
1992	—	—	—	—	—	—	—	—
1993	—	—	—	—	—	—	—	—
1994	88.9	8.3	1.3	1.6	89.9	7.8	1.6	0.8
1995	86.3	10.3	1.7	1.7	89.8	8.3	1.2	0.7
1996	84.6	13.2	0.9	1.3	86.6	11.1	1.7	0.7
1997	82.6	15.0	1.7	0.7	84.3	13.2	1.8	0.8

percent for softwoods. These differences are likely the result of changing sample constituents. The 1994 sample consisted only of trees in Michigan, Minnesota, and Wisconsin. In 1995, a reduced sample was taken in Michigan and Wisconsin, and an intensified sample was measured in Minnesota. Trees from Indiana were added in 1996 and trees from Illinois were added in 1997. The sample that will be measured in 1998 in Michigan, Minnesota, and Wisconsin will be the first remeasurements of a sample. This will begin to provide the change and trend information for that part of the subregion.

Foliage Transparency

For reporting the distribution of the transparency ratings, ratings are grouped into one of three categories. Normal contains those trees with dieback ratings of 0 to 30 percent; Moderate includes ratings from 31 to 50 percent; and Severe includes any ratings over 50 percent.

In New England, the percentage of trees with ratings in the Normal category has remained at about 98 percent, after a 1991 low of 93 percent for hardwoods and 95 percent for softwoods. Since the 1991 sample, the percentage of both hardwood and softwood trees in the Severe category has been less than 1 percent.

In the Mid-Atlantic states, the percentage of hardwood and softwood trees in the Normal category decreased with corresponding increases in the Moderate and Severe categories. The 1997 sample of trees in this subregion showed a return to previous percentage distributions. These differences occurred mainly as different states were included in the sample.

Table 3.—*Percentage distribution of live trees, 5.0 inches dbh and greater into three foliage transparency classes by year and species group*

	Hardwoods			Softwoods		
Year	Normal (0-30%)	Moderate (31-50%)	Severe (51+%)	Normal (0-30%)	Moderate (31-50%)	Severe (51+%)
	- - - - *Percent* - - - -			- - - - *Percent* - - - -		
New England						
1991	93.3	4.0	2.7	94.6	4.8	0.6
1992	97.2	2.0	0.8	97.8	1.4	0.8
1993	98.9	0.9	0.2	98.4	0.8	0.8
1994	98.7	1.0	0.3	99.2	0.7	<0.1
1995	98.9	0.6	0.5	99.0	0.9	0.1
1996	98.3	1.1	0.6	98.7	1.2	0.1
1997	98.3	1.7	0.0	98.9	1.1	0.0
Mid-Atlantic						
1991	99.7	0.3	0.0	95.2	2.4	2.4
1992	99.4	0.6	0.0	99.2	0.8	0.0
1993	98.0	1.6	0.4	98.2	1.2	0.6
1994	96.9	1.8	1.3	98.8	1.2	0.0
1995	92.5	5.8	1.7	90.6	8.4	1.0
1996	94.0	5.2	0.8	85.4	12.6	1.9
1997	98.3	1.4	0.4	95.5	3.6	0.9
Lake States						
1991	—	—	—	—	—	—
1992	—	—	—	—	—	—
1993	—	—	—	—	—	—
1994	97.7	1.1	1.2	98.0	1.8	0.2
1995	96.4	2.4	1.2	97.9	2.1	<0.1
1996	97.0	2.3	0.6	97.8	2.2	0.0
1997	94.4	5.0	0.6	95.0	4.8	0.2

In the Lake States, the percentage of hardwood and softwood trees in the Normal categories in the 1997 sample decreased with corresponding increases in the percentage of trees in the Moderate category, compared with previous samples. This is consistent with the differences in crown dieback for the same subregion.

Crown Density

For reporting the distribution of the density ratings, ratings are grouped into one of three categories. Poor contains those trees with density ratings of 0 to 20 percent; Average includes ratings from 21 to 50 percent; and Good includes any ratings over 50 percent.

In New England, the percentage of trees with ratings in the Good or Average categories remained at 96 percent or better. There was a trend in the samples to show a shift in the ratings from Good to Average until 1997 when the percentage of trees in the Good category rose slightly.

In the Mid-Atlantic states, the percentage of hardwood trees with ratings in the Good category decreased from 1991 to 1994. The percentage of hardwoods in the Good category increased in 1995 and 1996 but decreased again in 1997. The percentage of trees in the Poor category was never more than 3 percent. The percentage of softwood trees in the Good category decreased from 1991 to 1997. This decrease was accompanied by a corresponding increase in the percentage of trees in the Average category. As in the dieback and transparency results, differences in the distributions of the trees in the samples coincided with changes in the states included in the sample.

In the Lake States, the percentage of hardwood and softwood trees has fluctuated between the Good and

Table 4.—*Percentage distribution of live trees, 5.0 inches dbh and greater into three crown density classes by year and species group*

	Hardwoods			Softwoods		
Year	Poor (0-20%)	Average (21-50%)	Good (51+%)	Poor (0-20%)	Average (21-50%)	Good (51+%)
	- - - - - Percent - - - -			- - - - - Percent - - - -		
New England						
1991	3.4	41.7	54.8	1.8	38.3	59.9
1992	1.6	48.2	50.2	0.6	38.4	61.0
1993	2.2	53.7	44.1	1.9	51.4	46.7
1994	2.6	60.7	36.7	2.7	61.8	35.6
1995	2.7	58.5	38.8	2.3	64.3	33.4
1996	3.1	58.1	38.9	1.3	58.9	39.8
1997	3.1	52.6	44.3	3.6	54.1	42.2
Mid-Atlantic						
1991	1.1	30.2	68.7	0.0	16.7	83.3
1992	2.7	42.2	55.1	1.7	36.8	61.5
1993	1.6	43.1	55.3	2.4	63.3	34.3
1994	2.4	52.5	45.1	2.5	62.5	35.0
1995	2.5	37.3	60.2	1.5	63.1	35.5
1996	1.2	30.6	68.2	3.9	66.0	30.1
1997	1.3	47.9	50.8	3.6	66.1	30.4
Lake States						
1991	—	—	—	—	—	—
1992	—	—	—	—	—	—
1993	—	—	—	—	—	—
1994	2.9	52.9	44.2	1.5	47.2	51.3
1995	2.7	38.5	58.8	1.2	40.3	58.6
1996	2.1	41.3	56.6	1.5	48.6	50.0
1997	2.6	53.0	44.4	1.5	62.2	36.3

Average categories. For hardwoods, the percentage of trees in the Poor category ranged from 2 to 3 percent. For softwoods, the percentage of trees in the Poor category stayed constant at around 1.5 percent for all samples. As in the Mid-Atlantic subregion, fluctuations in the distributions coincided with the addition of new states to the sample in 1996 and 1997.

CONCLUSION

From this analysis of differences in the distributions of trees into various categories for the three crown variables—crown dieback, foliage transparency and crown density—the following conclusions can be drawn:

1. There are no large differences in the distributions among samples.
2. Yearly fluctuations are confounded by changing sample size and composition.
3. A fraction of the trees on the FHM plots are in severe condition, as measured by the three variables reported here.
4. Future analyses will need to control the sample to include only those plots that were present in all years up to 1995 when the reduction in number of plots measured each year occurred.
5. Now that the trees are being measured on a 4-year rotating basis, and data have been collected on most trees more than once, analyses will be able to assess trends in the same data sets, instead of trying to compare different yearly data sets.

LITERATURE CITED

USDA Forest Service. 1998. Forest health monitoring 1998 field methods guide. Triangle Park, NC: U.S. Department of Agriculture, Forest Service, National Forest Health Monitoring Program, Research.

Basic Truths for Planning and Executing an Inventory

John F. Bell

Abstract.—A number of basic truths are presented. The importance of carefully developing the objectives for an inventory is stressed. The use of permanent plots and temporary plots is covered. The necessity of obtaining a representative sample, training effectively, and collecting quality data is discussed. The future direction for forest inventories is suggested.

Thomas Edison said, "There is a better way for everything. Find it." An examination of the program for this meeting shows that through the many and varied speakers and their subjects we have the opportunity for better ways. We also have that opportunity as we share ideas with each other during breaks and activities throughout this conference.

We have the responsibility to be good stewards of our natural resources while working to meet our organization's objectives. We must have adequate data to properly manage these resources collected in a cost-effective and credible manner.

Today I will share some of my concerns and thoughts as well as the ideas of some of my forest inventory friends as I discuss basic truths of the planning and execution of a natural resource inventory.

My comments will primarily pertain to large-scale forest inventories. Natural resource inventories have become more and more complex. Foresters have traditionally put the emphasis on collecting data to manage the forest. The forest is composed of stands which are frequently referred to as polygons. A stand is defined by unifying characteristics such as species composition, age, tree size, and density. Normally, any measurable characteristic of the stand is put on a per unit basis. Thus, most inventories have been made to gather timber data. It is obvious that we have a growing need for information on wildlife, water, recreation, forage, and other non-timber values. This need has stimulated the development of integrated multiresource inventories. The non-timber values are usually much more difficult and expensive to assess than the timber values and are not well understood.

OBJECTIVES

Whether we are looking for water on Mars or designing a comprehensive inventory system, we must carefully determine our objectives. Regardless of the resource we are interested in, we must determine what data to collect to reach our objectives. We need to find out what information is available and which procedures and methods to use in obtaining the data that must be collected. Once we know these, we should ask if we have the finances, personnel, and time to achieve our objectives. All field procedures should be thoroughly tested before implementation. It is important to develop a plan for compilation and analysis before making the first field measurements and to test the compilation system.

A basic truth that may be overlooked is that the original objectives of the inventory often change between the time they are planned and the time they are executed. After the inventory has been completed, unanticipated questions may arise. It is most difficult to reassess data to answer questions the inventory and data collection were not designed to answer, again stressing the importance of proper planning. Save all data at the raw level for future recompilation. Do not throw anything away and do not round or classify until it is absolutely necessary.

Resource inventories must be adequately designed to reach the intended objectives. Sometimes the inventory is overdesigned, which causes it to be inefficient in achieving the planned use of the data. In designing the inventory, it is important to recognize that there are areas where little change occurs over time and other areas where changes are so rapid that the inventory information is soon outdated.

Sometimes it is most difficult to collect all the data needed to reach a given objective. A case in point is "The Oregon Plan for Salmon and Watersheds." This plan is designed to restore the healthy function of Oregon's natural aquatic systems. A speaker discussed this at a recent forestry meeting. He used the example of a Chinook salmon. At the end of his presentation he was

---

President, John Bell & Associates, Inc., and Professor Emeritus, College of Forestry, Oregon State University, Corvallis, OR, USA.

asked the question: "since a Chinook salmon spends most of its life in the ocean, what effort is being made to learn what happens to the salmon during that time?" His response after a reflective moment of silence was to tell a story. A man was down on his hands and knees under a light pole at night. A person came along and asked him what he was doing. He replied that he had lost his glasses. The next question was "where did you lose them?" His response was "over there." Why are you looking here? It is the only place I can see.

This emphasizes another basic truth. We need to thoroughly examine what the goals are for the inventory. We could develop nearly perfect stream habitat for salmon, yet accomplish little if we do not know what effect changes in the ocean conditions, fish harvest, or predators might have on the number of salmon returning to rivers and streams. In addition, we need to properly monitor salmon counts in the rivers before and after habitat restoration, as well as compare salmon counts in rivers that have had little or no disturbance with counts in rivers that have had degradation.

In planning for any natural resource inventory, we must have adequate knowledge of the population to be sampled and especially its dynamics. This knowledge is critical in designing a sampling system that will give a representative sample. This is difficult enough for forest populations that do not move. However, the problem is greatly compounded for animal, bird, and fish populations that have such varied patterns of movement.

RESOURCES

It is essential to have recent aerial photographs at a reasonable scale, current maps, trained personnel, proper equipment and computer capability to properly process the inventory data into information. The development of efficient field data recorders capable of functioning under a wide range of field conditions, including the ability to do editing in the field, has greatly enhanced the entire data recording process. Increased computer capacity makes it feasible to store more detailed data rather than just summaries. Actual stand tables or tree lists are particularly helpful for such activities as commercial thinning, midterm harvest planning, and preharvest timber cruising. Computer software programs need to be designed to meet the needs of the inventory system and not be just convenient for the programmers.

INVENTORY USERS

It is my experience that the people responsible for managing the area being inventoried should be heavily involved in all phases of the inventory. I have seen too many cases where the inventory was not used or not properly used when local personnel were not involved in the planning and execution of the inventory. Every possible effort should be made to have communication among those responsible for the field work, those analyzing the data, and the users. A periodic review of the inventory system by the inventory personnel and the users of the inventory is most important. This type of review also needs to be done whenever significant changes are being made in the inventory system. This is a particular problem with an ownership change. The new owner may have different objectives or have a different emphasis. Changes in measurement techniques, utilization standards, and type of inventory make it most difficult to integrate an existing inventory with a new one. This is also true when there are new or changing inventory requirements. This supports the concept that everyone has a vested interest in the inventory system.

MEASUREMENT CYCLE

An important issue needing careful consideration is the measurement cycle. A general session in this conference is devoted to annual forest inventory systems. This indicates the interest in a short measurement cycle. Rotation length and the extent of activities occurring have a major impact on the length of the measurement cycle. Some organizations collect data less frequently during that part of the rotation where little activity occurs. Another suggested method is to inventory a percentage of the ownership each year. For example, if the measurement cycle is 5 years, 20 percent of the ownership is inventoried each year. This makes it possible to have a permanent highly trained inventory staff. The inventory can be updated annually by using a model to project that part of the ownership that has not been measured. Again, it is essential to have the necessary funds, recent aerial photos, and trained personnel.

FOREST INVENTORIES

There are two major types of forest inventories: continuous forest inventory (CFI) and in-place or stand-based inventory. Considerable effort has been made since World War II in carrying out forest inventories. Many of us are anxious to hear what Ed Frayer and George Furnival have to say about the history of extensive forest inventories. There was considerable emphasis on permanent sample plots in the 1950's. Generally, the periodic remeasurement of permanent sample plots is effective in assessing changes in forest stands over time. Permanent plots are particularly useful in assessing changes due to growth, mortality, species composition, and catastrophic events. However, a CFI system is not effective without adequate financial support and trained personnel. These plots were often painted so that they were highly visible. As a result, sometimes these plots were treated differently than the surrounding area and the plots were no longer representative of the population.

14One of the major problems associated with permanent sample plots has been the change in the type of plot and in plot cluster configuration between measurements. I am aware of one organization that spent considerable funds to monument fixed-area plot clusters for relocation. They never remeasured the plots because they changed to a variable-plot cluster. These types of changes under the best of conditions make comparisons difficult. There has been considerable discussion about the merits or lack thereof in using variable plots as permanent plots. Actually each of the methods can be used effectively.

Plot clusters containing from 3 to 16 subplots have been used. The USDA Forest Service used three 1/5-acre plots and then changed to 10 sample points when they switched from fixed plots to variable plots. Recently the Forest Service's Forest Inventory and Analysis (FIA) program changed from variable plots to fixed plots. FIA has the responsibility for the inventory of the nation's forest and related resources. For plot clusters, the biggest cost is getting to the first subplot. There is considerable gain in measuring additional subplots while there. However, the most efficient plot cluster size is generally considered to be three to five subplots. There is a tendency to collect additional data while at the cluster location—the "as long as you are there" syndrome—which often proves to be not cost effective. It is particularly true with plot clusters. There has also been considerable discussion of what to do when one or more subplots fall in a different type. The latest recommendation is to not move these subplots.

Stand-based inventories do not measure changes as efficiently as a CFI system, but they do give better estimates of stand conditions. Plots not permanently marked for relocation are less costly. Thus, many organizations have opted for a stand-based inventory.

Various procedures for locating sample plots or points within a polygon have been in use over time by different organizations. Some have run a line of plots through the area that was judged to be representative of the area. One inventory forester instructed his crews to cover at least 70 percent of the polygon. A grid helps to eliminate bias due to plot location. A square pattern grid is most appropriate to use when the polygon is small and there is considerable variation throughout the area. However, some type of a rectangular pattern gives more sample plots for the distance walked compared to a square grid. Using a grid also tends to give a more representative sample.

SAMPLING PRECISION

It is important to establish a sampling precision level needed for the overall inventory. This precision level should be appropriate for meeting the objectives of the inventory. A much lower precision level is needed at the polygon level, but the precision must be high enough so that the results are useful. We need to be mindful that it requires four times as many sampling units to reduce the sampling error by 50 percent. We often neglect to determine the critical components of what we are measuring. We should have reasonable estimates of the coefficient of variation of these critical components so that they can be sampled at an appropriate precision. In some cases, polygon size rather than the variation within the polygon has been used for determining sample size. Samplers need to develop the ability to estimate the coefficient of variation.

Surprisingly, many software programs do not calculate the sampling error and coefficient of variation for the component parts. Too many inventory foresters do not understand the difference between sampling error and coefficient of variation. It is important to know by checking actual data rather than to rely on what is commonly believed within an organization. In one project, we examined the coefficient of variation of an item for several samples. The coefficient of variation ranged from 2.5 to 6.7 percent. Thus, only a few observations were needed compared to the considerable time and effort the company was spending. Something that should be done more often is to change an item and observe the effect. If nothing important has changed, it is obvious that the system is insensitive to that measurement.

STRATIFICATION

There is considerable precision gain in classifying (stratifying) resource populations into homogenous units. In a forest inventory, the unit is a stand of similar characteristics. The purpose of stratifying is to reduce the variation within the polygon and to increase the precision of the population estimate. Sometimes there is a tendency to overstratify. We need to be mindful that it is necessary to accurately determine the acreage of each stratum or the gain in precision is lost due to incorrect acreage.

EDGE EFFECT

Another basic truth in forest sampling involves obtaining a representative sample of the outer edge of a polygon. There is often considerable difference in stand conditions between the perimeter of a polygon and its interior. Sometimes inventory foresters insist on moving in two chains before taking a plot. A one-chain-wide area on the perimeter of a square 40-acre unit represents 19 percent of the 40 acres (fig. 1). It is obvious that the perimeter of a polygon increases as the shape of the polygon becomes more and more irregular. Figure 2 shows an irregular shaped area 10.1 acres in size. A one-chain-wide area on the perimeter is 46.5 percent of the total area. Figure 3 shows an irregular shaped area 30.1 acres in size. A one-chain-wide area on the perimeter is 27.9 percent of the total area. Thus, these two areas would need to have 46.5

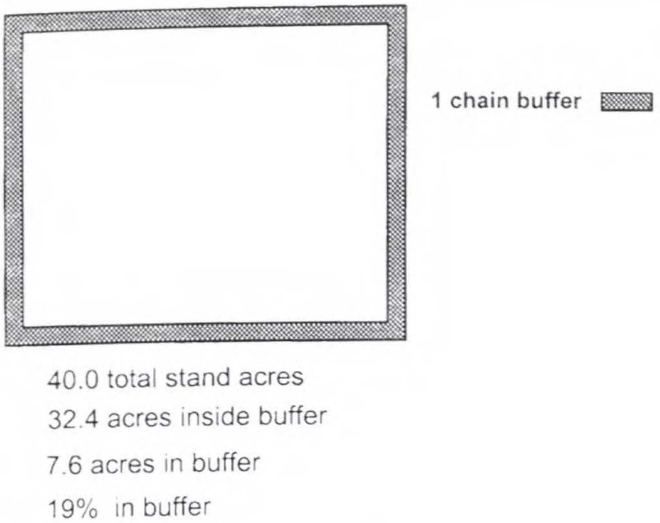


Figure 1.—*Illustrates a square 40-acre unit. A one-chain-wide area on the perimeter represents 19 percent of the unit.*

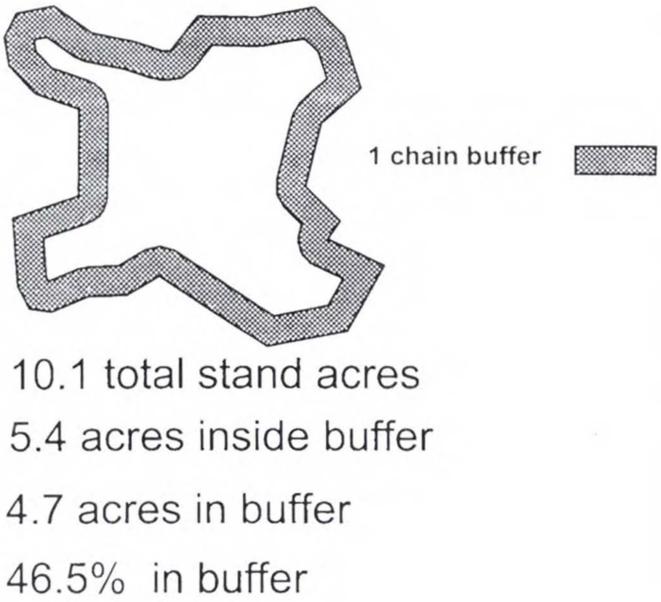


Figure 2.— *Shows an irregular shaped unit 10.1 acres in size. A one-chain-wide area on the perimeter represents 46.5 percent of the unit.*

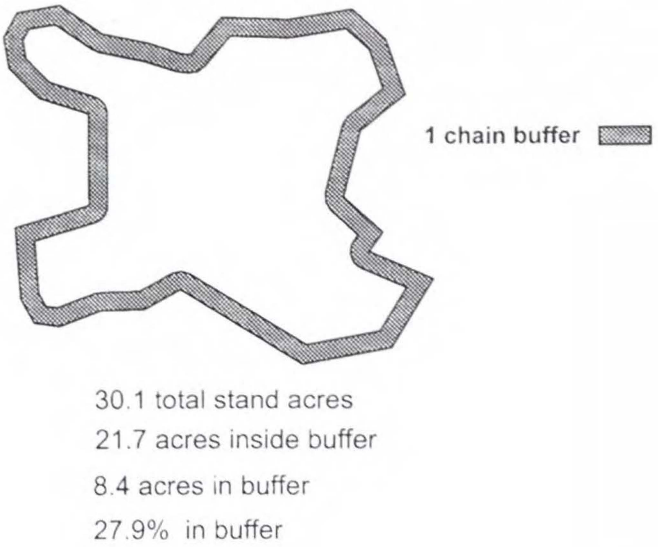


Figure 3.—*Shows an irregular shaped unit 30.1 acres in size. A one-chain-wide area on the perimeter represents 27.9 percent of the unit.*

and 27.9 percent of the sample plots, respectively, in each of these areas to have a representative sample. It is my opinion that most of us are not aware of the magnitude of the problem of edge effect. These various sized and shaped polygons illustrate the large percentage of the total area that a one-chain-wide area on the perimeter represents. This certainly points out the difficulty of obtaining a representative sample of the area on the perimeter of a polygon. It also illustrates the challenge of achieving a representative sample in odd shaped areas such as riparian zones.

ACCURATE MEASUREMENTS

Regardless of the inventory system used, accurate measurements are critical. Personnel should be highly trained and conscientious. The only way to achieve uniform results is through intensive and continuous training of field crews. In addition to training, accurate field measurements depend on quality instruments and their careful use. It is important to check instrument accuracy before going to the field. Along this line, it is preferable to use full-time field personnel rather than part-time crews. Likewise it is desirable to make accurate measurements rather than estimates and judgment calls. Generally it is better to make fewer accurate measurements rather than a greater number of estimates. Those conducting resource inventories need to be on the watch for improved equipment. The challenge is to obtain the most efficient equipment to meet the resource inventory requirements. It is also important to develop written procedures that ensure consistent measurements. In addition to having carefully written procedures, it is essential to precisely document all analyses and results. It is critical to report the reliability of all statistical data. This is often neglected in reports by secondary users, which can lead to faulty conclusions. Another problem is when inventory information is interpreted and used for purposes other than that for which it was designed. The followup to training is an effective auditing program. Foresters call this check cruising although most others refer to it as quality control. The auditing program is used to see if the person knows the procedures and how to make and record all the needed measurements. This is usually accomplished by accompanying the person while the work is being done under various conditions. The second aspect could be referred to as an independent audit. This is done by visiting a small percentage of randomly selected plots. It is important to understand which errors in measurements cause significant changes in the results. For instance, errors in diameter measurements have small consequences compared to height measurements for computing volume in variable plot sampling. Yet, there is a tendency to carefully check diameters since it is easy to do. The point is that the items that cause change in results must be checked, not just the ones that are easily checked. The concept is that the inventory person knows that any given plot can be checked regardless of location. This means you do not check only the plots close to the road. This encourages consistent high performance.

FOREST HEALTH MONITORING

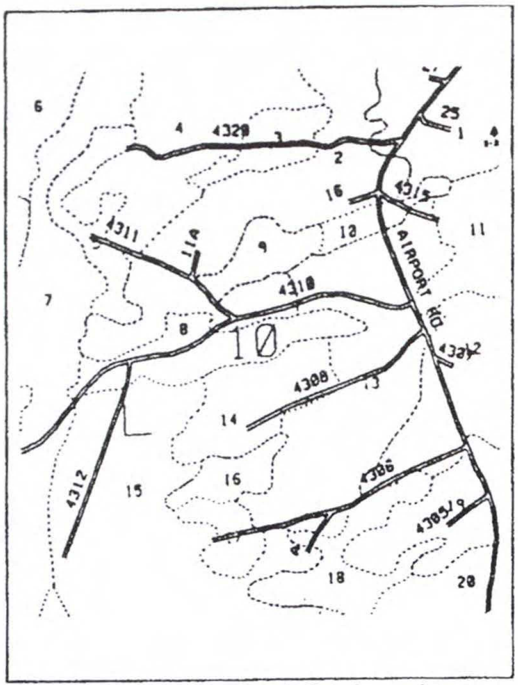
We hear much about forest health monitoring (FHM). Activities associated with forest health monitoring include protecting sensitive areas, planting riparian zones, reforestation, controlling erosion, rehabilitating streams, thinning overstocked forests, disturbances affecting the health of the forest ecosystem, and restoring wildlife habitat. Achieving success in inventorying these activities requires considerable planning and clearly defined objectives. There are many challenges such as selecting attributes to monitor to detect change, choosing a sampling design, and determining sampling intensity.

A basic truth is that there is much to be gained by having uniform procedures and standards throughout an organization. However, some of the objectives of Forest Inventory and Analysis and Forest Health Monitoring are different. It is my opinion that FIA and FHM should not sacrifice important objectives of one or the other in the process of standardizing procedures.

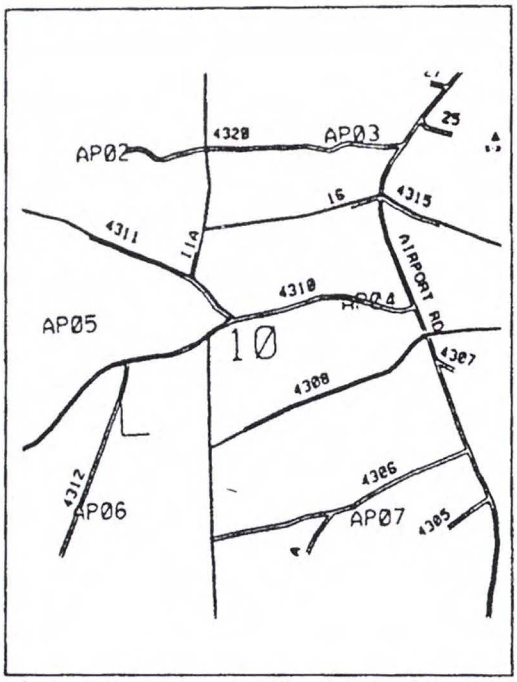
HARVEST UNIT-BASED INVENTORY

A basic truth associated with harvest units is that the harvest unit boundaries are often changed from the time they are selected until the harvest is completed. This causes many problems. One possible solution is the adoption of a harvest unit-based inventory.

In the 1980's, the Simpson Timber Company examined what they wanted from their inventory system. Management asked the inventory department to evaluate the long-term effect of various cutting scenarios on the future supply and quality of wood that would be available to their mills (Naccarini 1990). Figure 4 compares their former cover type map with their new harvest unit blocks.



In 1978 a cover type was defined as a homogeneous stand of timber with similar species, stocking, age and site class.



Today, cover types are defined as blocks of timber that are expected to be managed as one unit in the future.

Figure 4.—*Compares Simpson Timber Company's former cover type map with their new harvest unit blocks.*

"The harvest unit information is maintained by our Geographic Information System. Each unit has a unique identification number which ties directly to our silvicultural activity tracking system, long term harvest scheduling system, log accounting system, and of course, our entire forest inventory system. The harvest unit database stores the characteristics of each unit, such as, primary species, average site index, total age, relative density. Species information including trees/acre, quadratic mean diameter, and current volume/acre are also stored within this table. The system also keeps track of the projected volumes at the scheduled year of harvest." (Naccarini 1995). The harvest unit-based inventory is working well for the Simpson Timber Company. The system implies that the operational foresters are able to define future harvest units with reasonable accuracy. Many companies have had problems stemming from changes in planned harvest unit boundaries.

GEOGRAPHICAL INFORMATION SYSTEM

GIS should be considered for what it has to offer to enhance your current inventory system. Initially GIS was oversold. The maps looked great but the emphasis was on maps rather than integrating the inventory data. In the system are two databases, one being the resource inventory database that describes what is there. The other is the spatial coordinate data showing where it is located. All other applications are derived from these two components. These two components can be organized into separate layers that describe such things as the road system, water drainages, stand polygons, ownership, and planimetric and topographical features.

GIS software allows map features to be combined in various ways. These maps can be made at almost any scale. In the resource database would be such things as volume per acre, basal acre per acre, and any other stand information. GIS combining spatial and tabular databases makes possible the selection of all stands available for a certain activity such as thinning or harvesting, according to whatever criteria or distinguishing features you might want to use. Combining the map and resource bases, GIS is a highly effective tool for analyzing and establishing short- and long-range plans. In addition, GIS is valuable in keeping an inventory system current.

FUTURE DIRECTION FOR RESOURCE INVENTORIES

The basic truth here is that we are always striving for better ways to carry out an inventory. The three papers being presented later this morning discuss the very large forest resources inventory being conducted by the British Columbia Forest Service. This inventory certainly suggests the direction for future resource inventories. The province was divided into about 40 regions. An estimate was made of the volume in each polygon based on the data from the previous inventory. Approximately 200 polygons were selected in each region from an ordered list with a random start. Data are collected within each of the selected polygons. The total of all the estimates from all the polygons within a region are adjusted by the relationship between estimated and the measured data from the selected polygons. This British Columbia inventory is an excellent way to conduct a forest resources inventory.

CONCLUDING REMARKS

In conclusion, I encourage each of us to accept Thomas Edison's challenge, "There is a better way for every thing. Find it." May the things you learn and discuss during this conference help you find better ways to carry out your responsibilities.

ACKNOWLEDGMENTS

The following people reviewed this paper: James T. Bones, retired USDA Forest Service, Yachats, OR, USA, and David D. Marshall, College of Forestry, Oregon State University, Corvallis, OR, USA.

LITERATURE CITED

Naccarini, M. 1990. Long range harvest planning with GIS. Inventory and Cruising Newsletter 11. John Bell & Associates, Corvallis, OR.

Naccarini, M. 1995. A harvest unit based inventory system. Inventory and Cruising Newsletter 30. John Bell & Associates, Corvallis, OR.

A Comparison of Sample Unit Designs in the National Inventory of the U.S.

B.E. Borders, G.H. Brister, N. Grahl, B.D. Shiver, and C.J. Cieszewski

Abstract.—The Forest Inventory and Analysis (FIA) program of the USDA Forest Service has adopted a new sampling unit for the national forest inventory of the U.S. We compared this new sampling unit with five other sampling units. Data from natural loblolly pine (*Pinus taeda* L.) stands in the Georgia piedmont show that all sample units produce reasonable estimates for the pine overstory in this stand type. However, plot clusters typically used by FIA to sample trees in the 1.0 to 4.9 inch dbh range can produce seriously biased estimates. Use of a single, subjectively chosen "site" tree, as done by FIA field crews, results in serious overestimation of site index for this stand type.

The Forest Inventory and Analysis (FIA) program of the USDA Forest Service is implementing significant procedural changes in various regions of the U.S.; e.g., the Annual Forest Inventory System (AFIS) in the lake states region, and the Southern Annual Forest Inventory System (SAFIS) in the southern region. These annual inventory systems have been adopted to improve the quality and timeliness of standing forest inventory data. Essentially, these annual inventory systems subsample a proportion of permanent ground locations each year and update the remaining permanent ground locations with some type of model or other updating procedure. One of the changes that was adopted along with these annual inventories is the use of a new sample unit design at each permanent ground location. FIA has used several different types of sampling units throughout the past 40 plus years: (1) a single fixed-area circular plot; (2) a single 10-BAF point; (3) a cluster of ten 37.5-BAF points for large diameter trees (dbh >= 5.0 inch) and ten 1/300-acre plots for small diameter trees (dbh from 1.0 to 4.9 inches); and (4) a cluster of five 37.5-BAF points for large diameter trees and five 1/300-acre plots for small diameter trees. The newest ground-based sample unit is a cluster of four 1/24-acre sample plots for large diameter trees and four 1/300-acre sample plots for small diameter trees.

Choice of sampling unit could have a large impact on resulting sample estimates for a given forest inventory. In fact, it is possible, indeed very probable, to carry out an inventory using different types of sampling units at the same exact ground locations and obtain different estimates of population parameters. This difference may be quite small or it may be very large depending on the specific population elements that are included in each sampling unit.

We conducted a field study to evaluate the utility of six different sampling units for characterizing natural loblolly pine (*Pinus taeda* L.) stands in the Georgia piedmont.

STUDY AREA AND FIELD METHODS

Bishop F. Grant Memorial Forest is located in the Georgia piedmont in Putnam County. This forest, owned and managed by the Daniel B. Warnell School of Forest Resources of the University of Georgia, is approximately 10,000 acres in size and contains a host of stand types ranging from hardwood bottoms to intensively managed loblolly pine plantations. For the study described in this paper, we sampled natural loblolly pine stands ranging in age from 20 to 80 years old. These stands are characterized by a pine overstory with a relatively small hardwood component in the understory.

To evaluate how various sampling units represent a given population, population parameters must be known. This is possible when simulation studies are done; however, when working with real world stand data, it is very difficult, if not impossible, to know population parameters. To overcome this problem we established a series of 49 square plots, each approximately 1-1/2 acres in size, as our "population." Each plot was 260 feet square so that all sampling units could be contained within the plot. On each plot, all trees were measured for dbh to the nearest 0.1 inch using a diameter tape, classified according to their crown position (dominant, codominant, intermediate, suppressed), and evaluated for the presence of fusiform rust (*Cronartium fusiforme* Hedge. And Hunt ex Cumm.). Furthermore, the total height of the first tree and every fourth tree thereafter in each 1-inch dbh class was measured to the nearest foot with a hypsometer. The

---

Professor, Professor, Research Assistant, Professor, and Assistant Professor, respectively, Daniel B. Warnell School of Forest Resources, The University of Georgia, Athens, GA, USA.

number of 16-foot logs was estimated to the nearest one-half log for each pine tree large enough to contain at least one log. A subset of dominant and codominant trees were cored for age at 1 foot and at 4.5 feet from ground level.

Six different sampling units were established in the interior of each of the 49 large plots. The sampling units were (1) cluster of five 37.5-BAF sample points (fig. 1) as used by the USDA Forest Service[1] ; (2) a single 7.5-BAF sample point located at the center of the large plot; (3) cluster of four 1/24-acre sample plots (fig. 2) as used by the Forest Service; (4) a single 1/6-acre circular sample plot located at the center of the large plot; (5) a single 1/10-acre circular sample plot located at the center of the large plot; and (6) a single 1/20-acre circular sample plot located at the center of the large plot. At each point of the five-point cluster, a 37.5-BAF selection criterion was used to select trees 5.0 inches dbh and larger. Additionally, a 1/300-acre circular sample plot, centered at each of the five points, was used to select trees ranging in dbh from 1.0 to 4.9 inches. On each 1/24-acre circular sample plot of the four-plot cluster, trees 5.0 inches dbh and larger were sampled. Additionally, at the center of each of these 1/24-acre sample plots, a 1/300-acre circular sample plot was used to select trees ranging in dbh from 1.0 to 4.9 inches. On the four other sample units listed above, all selected trees were included regardless of dbh. Note that the 1/6-acre circular sample plot was chosen because this is the same area sampled by the cluster of four 1/24-acre sample plots. The single 7.5-BAF point was used because it corresponds to the same sampling intensity as the cluster of five 37.5-BAF points. The 1/10- and 1/20-acre plots were used to evaluate the usefulness of smaller fixed-area sampling units. Note: all trees selected on each of the sampling units were measured for dbh to the nearest 0.1 inch with a diameter tape, classified as to crown position, and evaluated for the presence of fusiform rust. Additionally, total heights were subsampled and number of 16-foot logs to the nearest half log were estimated as described above.

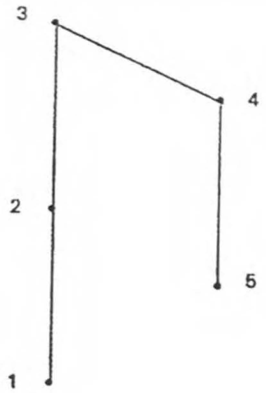


Figure 1.—*Layout of five-point cluster sampling unit. At each point a 37.5-BAF prism is used to select sample trees 5.0 inches dbh and larger. In addition, a 1/300-acre fixed-area sample plot centered at each point is used to select sample trees 1.0 to 4.9 inches dbh. Note—distance from point to point is 70 feet. The azimuth from point 1 to 2 and from 2 to 3 is 0 degrees, the azimuth from point 3 to 4 is 120 degrees, and the azimuth from point 4 to 5 is 180 degrees.*

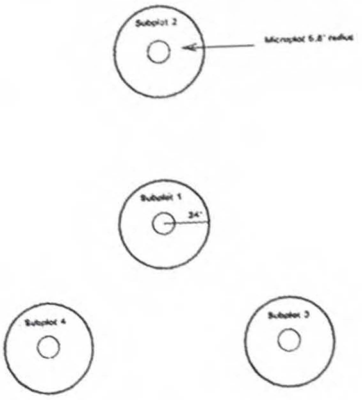


Figure 2.—*Layout of four-plot cluster. On each 1/24-acre subplot, all trees 5.0 inches dbh and larger are selected as sample trees. At the center of each subplot, a 1/300-acre microplot is used to select sample trees between 1.0 and 4.9 inches dbh. Note—distance from subplot center to subplot center is 120 feet. The azimuth from subplot 1 to 2 is 0 degrees, the azimuth from subplot 1 to subplot 3 is 120 degrees, and the azimuth from subplot 1 to subplot 4 is 240 degrees.*

DATA SUMMARIZATION AND ANALYSIS

All data for each large sample plot as well as for the six sample units were summarized for pine and hardwood separately as well as for both species groups combined for trees per acre (TPA), basal area per acre in square feet (BA), total volume per acre in cubic feet (VOL), and proportion of pine with fusiforme rust (R). Scribner (SCRIB) board foot volume was calculated for pine trees having one or more logs, using the equations developed by Wiant and Castaneda (1978). Additionally, average site index for each large plot was calculated using the function by Martin (1998) with all dominant and codominant trees that were measured for height and age at 1 foot from ground level. Site index on the cluster of five points and for the cluster of four fixed-area plots was calculated using the height and age of a single dominant or codominant tree chosen by the field crew as being representative of the other dominant and codominant trees in the stand. This method was used to simulate the field procedures on FIA sample plots. Site index was also estimated for each of the sampling units using all dominant and codominant trees that were measured for height and age on the sampling unit.

---

[1] USDA Forest Service. Field instructions for the seventh forest inventory of Georgia. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Forest Research Station. 146 p. Unpublished Draft.

Separate height—dbh models were developed for each of the 49 large plots. These models were used to estimate height for those trees not measured for height in the field. Cubic foot volume equations for natural loblolly pine were taken from Clarke and Saucier (1990) and for the hardwood species from Clarke *et al.* (1986). Note that separate estimates of each characteristic were obtained for trees from 1.0 to 4.9 inches dbh and for trees 5.0 inches dbh and larger to avoid the difficulties of combining estimates from the different types of sampling units used to select trees in these two size classes in the point and plot clusters. Of course, this difficulty does not exist for the sampling units that consist of a single point or fixed-area plot for which all trees were selected without regard to dbh.

All of the large 260-foot square plots were combined to establish our hypothetical population. For each stand measure described above, the population parameter was obtained using the 100 percent census of these 49 plots. For each of the six different sampling units, each stand measure was estimated using the trees selected and measured on the sampling unit. Note that the height—dbh regressions fitted to the large plot were used to estimate heights for trees that were not measured for height on each of the sampling units within each large plot. This was done to avoid confounding the analysis with height—dbh relationships that were not equally well established. The estimates obtained for each sampling unit were averaged across the 49 plots as if they represented a random sample of sampling units from the population. For each stand parameter, the estimate, standard error, and 95 percent confidence interval were calculated and compared with the population value.

RESULTS

Population values and sample estimates for each sample unit for TPA, BA, VOL, R, and SCRIB for the pine component greater than 5.0 inches dbh for these natural loblolly pine stands show that all sampling units provide sample estimates relatively close to the population parameter (tables 1-5). In fact, all sampling units produce 95 percent confidence intervals that contain the population parameter for all of these stand characteristics except the estimates from the 1/20-acre sampling unit. The variability of the estimates is smaller for the 1/6-acre plot compared with the cluster of four 1/24-acre plots, as well as smaller for the 7.5-BAF point than for the cluster of five 37.5-BAF points. This should be expected since the clusters sample a larger area than the single plot or point. The variability of the single 1/10-acre plot was smaller than or only slightly larger than the variability associated with the cluster of 1/24-acre plots. Clearly, estimates from the single 1/20-acre plot had a great deal more variability associated with them than estimates from all other sampling units.

The hardwood understory in these stands is patchy and consequently highly variable. Estimates of the average TPA and BA for hardwood trees from 1.0 to 4.9 inches dbh indicate that the 1/6-acre, 1/10-acre, and 1/20-acre sample plots and the cluster of 1/24-acre plots were more representative of the small hardwood component of these stands than the single point or point cluster (tables 6-7).

Table 1.—*Average number of loblolly pine trees per acre 5.0 inches dbh and greater for the 76-acre population and the estimates of this characteristic for 49 sample plots using various sampling unit configurations*

Population Value – 61.5 trees/acre

Sampling unit	Mean	Standard error	95% Confidence interval Lower limit	95% Confidence interval Upper limit	Population value in the Interval?
		- - - - - - - *Trees/acre* - - - - - - -			
4 Plot Cluster	64.5	4.8	54.8	74.2	YES
1/6 Acre Plot	65.5	3.4	58.6	72.4	YES
5 Point Cluster	68.8	6.1	56.6	81.1	YES
7.5 BAF Point	63.8	4.1	55.6	72.1	YES
1/10 Acre Plot	65.5	4.2	57.0	74.0	YES
1/20 Acre Plot	71.4	4.9	61.5	81.4	YES

Table 2.—*Average basal area per acre for loblolly pine trees 5.0 inches dbh and greater for the 76-acre population and the estimates of this characteristic for 49 sample plots using various sampling unit configurations*

Population value – 64.3 square feet/acre

Sampling unit	Mean	Standard error	95% Confidence interval Lower limit	95% Confidence interval Upper limit	Population value in the interval?
	- - - - - - - - *sq ft/acre* - - - - - - -				
4 Plot Cluster	67.1	3.5	60.2	74.1	YES
1/6 Acre Plot	68.2	2.9	62.4	74.1	YES
5 Point Cluster	68.7	3.7	62.0	75.7	YES
7.5 BAF Point	66.3	3.0	60.3	72.2	YES
1/10 Acre Plot	66.1	3.7	58.7	73.5	YES
1/20 Acre Plot	73.4	4.2	65.0	81.8	NO

Table 3.—*Average cubic foot volume per acre for loblolly pine trees 5.0 inches dbh and greater for the 76-acre population and the estimates of this characteristic for 49 sample plots using various sampling unit configurations*

Population value – 2250 cubic feet/acre

Sampling unit	Mean	Standard error	95% Confidence interval Lower limit	95% Confidence interval Upper limit	Population value in the interval?
	- - - - - - - - *cu ft/acre* - - - - - - -				
4 Plot Cluster	2,318	128	2,059	2,576	YES
1/6 Acre Plot	2,388	115	2,155	2,621	YES
5 Point Cluster	2,380	125	2,127	2,632	YES
7.5 BAF Point	2,315	114	2,084	2,546	YES
1/10 Acre Plot	2,316	140	2,034	2,599	YES
1/20 Acre Plot	2,562	159	2,240	2,883	YES

Table 4.—*Average proportion of fusiform rust for loblolly pine trees 5.0 inches dbh and greater for the 76-acre population and the estimates of this characteristic for 49 sample plots using various sampling unit configurations*

Population value – 0.23

Sampling unit	Mean	Standard error	95% Confidence Interval Lower limit	95% Confidence Interval Upper limit	Population value in the interval?
	- - - - - - - *Proportion infected* - - - - - -				
4 Plot Cluster	0.26	0.02	0.21	0.31	YES
1/6 Acre Plot	0.24	0.03	0.20	0.29	YES
5 Point Cluster	0.27	0.03	0.20	0.33	YES
7.5 BAF Point	0.25	0.02	0.20	0.30	YES
1/10 Acre Plot	0.25	0.03	0.19	0.30	YES
1/20 Acre Plot	0.27	0.04	0.19	0.35	YES

Table 5.—*Average Scribner board foot volume for the 76-acre natural loblolly pine population and the estimates of this characteristic for 49 sample plots using various sampling unit configurations*

Population value – 3,982 board feet/acre

Sampling unit	Mean	Standard error	95% Confidence interval		Population value in the interval?
			Lower limit	Upper limit	
	- - - - - - -	- bd ft/acre -	- - - - - - -		
4 Plot Cluster	4,466	393	3,672	5,260	YES
1/6 Acre Plot	4,155	296	3,557	4,753	YES
5 Point Cluster	4,229	299	3,624	4,833	YES
7.5 BAF Point	4,163	301	3,556	4,771	YES
1/10 Acre Plot	4,035	361	3,306	4,764	YES
1/20 Acre Plot	4,289	429	3,423	5,155	YES

Table 6.—*Average number of hardwood trees per acre 1.0 to 4.9 inches dbh for the 76-acre population and the estimates of this characteristic for 49 samples using various sampling unit configurations*

Population value – 55.1 trees/acre

Sampling unit	Mean	Standard error	95% Confidence interval		Population value in the interval?
			Lower limit	Upper limit	
	- - - - - - -	- trees/acre -	- - - - - - -		
4 Plot Cluster	50.5	11.2	27.9	73.1	YES
1/6 Acre Plot	48.2	6.8	34.4	62.1	YES
5 Point Cluster	2.4	1.7	0	5.9	NO
7.5 BAF Point	6.3	5.1	0	16.6	NO
1/10 Acre Plot	47.8	8.1	31.3	64.2	YES
1/20 Acre Plot	51.8	9.4	32.8	70.9	YES

Table 7.—*Average basal area per acre (sq ft) for hardwood trees 1.0 to 4.9 inches dbh for the 76-acre population and the estimates of this characteristic for 49 sample plots using various sampling unit configurations*

Population value – 1.7 square feet/acre

Sampling unit	Mean	Standard error	95% Confidence interval		Population value in the interval?
			Lower limit	Upper limit	
	- - - - - - -	- sq ft/acre -	- - - - - - -		
4 Plot Cluster	1.4	0.6	0.2	2.6	YES
1/6 Acre Plot	1.6	0.2	1.1	2.0	YES
5 Point Cluster	0.3	0.2	0.0	0.6	NO
7.5 BAF Point	0.5	0.3	0.0	1.1	NO
1/10 Acre Plot	1.4	0.2	0.9	1.9	YES
1/20 Acre Plot	1.5	0.3	0.9	2.0	YES

Site index estimates (base age 50) were calculated for the pine component of these stands. The "population" value was determined by using all dominant and codominant trees that were measured for total height and cored for age at 1 foot from the ground. The sample unit values were calculated for each sample unit using all dominant and codominant trees measured for total height and cored for age at either 1 foot or 4.5 feet off the ground. Note that the average difference of 3 years between age at 4.5 feet and age at 1 foot was added to ring counts from 4.5 feet. Thus, each sampling unit had a site index value calculated from a different number of measured trees. The estimates indicate that all sampling units produced reasonable site index estimates using this method (table 8).

Standard field procedures used on FIA ground locations require field crews to select a single tree to use in obtaining an estimate of site index for the sampling location. This tree is measured for total height and cored for age and used to determine site index. This estimate of site index is very weak at best because it is based on a single tree. In fact, Johnson and Carmean (1953) showed that the use of three sample trees to estimate site index for Douglas-fir stands resulted in a bound on the estimated site index of more than 25 feet. Comparison of estimated site index values from the single "site" tree selected by the field crew with the average of the large sample of dominant and codominant trees measured for total height and cored for age at 1 foot from the ground on each large sample plot shows that differences at a given location are as large as 26.8 feet (table 9). The average site index for the hypothetical population was 80.6 feet, while the average site index calculated from the single site tree at each location was 86.7 feet. The 95 percent confidence interval for this estimate has a lower value of 84.1 feet and an upper value of 89.3 feet. Clearly, there is a great deal of error associated with estimating site index with a single site tree.

DISCUSSION

All sampling units produced reasonable estimates of pine overstory population parameters investigated for natural loblolly pine stands in the Georgia piedmont. The clusters of plots and points resulted in more highly variable estimates than a single point or single fixed-area sample plots. The 1/10-and 1/20-acre fixed-area sample plots produced more variable estimates than the 1/6-acre fixed-area sample plot. However, confidence intervals for these smaller fixed-area sample plots enclosed the population parameter for all stand characteristics except for the estimate of basal area per acre for the 1/20-acre sample plot.

Estimates of the small hardwood understory component of these stands were highly variable for all sampling units. The fixed-area plot cluster as well as all single fixed-area plots produced confidence intervals that enclosed the population parameter for both trees per acre and basal area per acre. However, the cluster of points and single point produced very poor biased estimates for both of these characteristics. The difference in the accuracy of the estimates of the understory hardwood component for the plot cluster and point cluster seems illogical. Both methods made use of 1/300-acre fixed-area sample plots. In fact, the cluster of points uses five of these plots while the cluster of plots uses four. Thus, even with more intensive sampling, the point cluster resulted in poor estimates of number of small hardwoods in the understory. As stated above, the understory hardwood component was patchy and very variable. A total of 33 hardwood trees from 1.0 to 4.9 inches dbh were tallied on the 49 clusters of 1/300-acre plots associated with the four-plot clusters, while only 2 hardwood trees from 1.0 to 4.9 inches dbh were tallied on the 49 clusters of 1/300-acre plots associated with the five-point clusters. Clearly,

Table 8.—*Average site index (base age 50) for the 76-acre natural loblolly pine population and the estimates of this characteristic for 49 sample plots using various sampling unit configurations*

Population value – 80.6 feet

Sampling unit	Mean	Standard error	95% Confidence interval Lower limit	95% Confidence interval Upper limit	Population value in the interval?
	feet				
4 Plot Cluster	81.4	1.1	79.2	83.6	YES
1/6 Acre Plot	82.2	1.2	79.9	84.6	YES
5 Point Cluster	82.6	1.0	80.6	84.7	YES
7.5 BAF Point	84.9	1.6	81.6	88.2	NO
1/10 Acre Plot	81.7	1.3	79.0	84.4	YES
1/20 Acre Plot	80.7	1.4	77.7	83.6	YES

Table 9.—*Site index estimates (feet) for each large sample plot calculated with a single site tree selected by the field crew (SI-Crew) as well as calculated with a the large sample of dominant and codominant trees measured for total height and age (SI-Large)*

Plot	SI-Crew	SI-Large	Difference
1	102.1	82.4	19.7
2	104.8	83.0	21.8
3	87.5	88.2	-0.7
4	81.3	76.5	4.8
5	82.5	92.0	-9.5
6	101.2	90.0	11.2
7	89.3	88.2	1.1
8	102.6	98.3	4.3
9	88.7	85.9	2.8
10	88.9	87.5	1.4
11	106.4	79.6	26.8
12	94.9	88.0	6.9
13	76.8	75.2	1.6
14	72.4	73.3	-0.9
15	81.8	75.3	6.5
16	88.1	84.8	3.3
17	94.3	80.8	13.5
18	85.5	74.6	10.9
19	87.5	85.3	2.2
20	76.4	79.5	-3.1
21	74.5	76.9	-2.4
22	82.9	84.0	-1.1
23	93.9	75.6	18.3
24	93.0	78.9	14.1
25	82.2	82.5	-0.3
26	74.8	68.5	6.3
27	76.3	82.1	-5.8
28	80.8	72.3	8.5
29	84.3	79.9	4.4
30	80.3	70.4	9.9
31	72.9	74.3	-1.4
32	86.1	59.9	26.2
33	76.3	61.3	15.0
34	91.0	78.5	12.5
35	78.8	73.8	5.0
36	98.5	84.4	14.1
37	76.6	81.3	-4.7
38	84.9	80.0	4.9
39	82.9	81.9	1.0
40	75.4	82.5	-7.1
41	83.7	81.4	2.3
42	83.6	91.3	-7.7
43	92.4	93.3	-0.9
44	88.7	86.4	2.3
45	94.3	87.9	6.4
46	107.6	91.2	16.4
47	88.8	72.9	15.9
48	81.9	68.5	13.4
49	88.2	81.0	7.2

placement of the point clusters resulted in a very non-representative sample of the population. This is the danger associated with using such a small sampling unit to sample highly variable populations.

Site index estimates based on a single "site" tree selected by the field crew consistently overpredicted estimates based on a large number of sample trees. These overestimates resulted in a positive bias of approximately 6 feet across our hypothetical population. However, when several dominant and codominant trees from each sampling unit were used to estimate site index, resulting estimates were very close to the population value. It seems logical that an overestimate of site index will result from the choice of a single site tree since field crews will usually be inclined to choose the tallest tree in the neighborhood of the sample plot.

Based on our field study, all sampling units evaluated were adequate for estimating the pine overstory component of mature natural loblolly pine stands. However, there is higher variability associated with smaller fixed-area plots and with clusters of small fixed-area plots or large BAF points. Use of four or five 1/300-acre sample plots to estimate highly variable hardwood understories in this stand type showed that resulting estimates were highly variable and potentially seriously biased. Site index estimates based on a single subjectively chosen site tree result in serious overestimates of site index. This will most likely present a problem when some type of plot update procedures are implemented for the AFIS and SAFIS inventory designs.

RECOMMENDATIONS

Based on this field study, we believe that the current sample unit design consisting of four 1/24-acre plots will produce reasonable unbiased estimates of important stand characteristics. However, the use of the very small 1/300-acre sample plots for estimating highly variable stand understories is questionable. We recommend that consideration be given to measurement of all trees falling on the 1/24-acre sample plots without regard to diameter. This should result in better understory estimates that will likely be necessary for model update procedures for AFIS and/or SAFIS. Finally, we believe it is prudent to measure additional dominant and codominant trees for total height and age so that realistic site index estimates can be obtained. If two dominant or codominant trees were obtained on each of the four subplots, the site index estimate would be realistic and useful in plot update procedures.

LITERATURE CITED

Clark, A., III; Phillips, D.R.; Frederick, D.J. 1986. Weight, volume, and physical properties of major hardwood species in the Piedmont. Res. Pap. SE-255. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Research Station. 74 p.

Clark, A., III; Saucier, J.R. 1990. Tables for estimating total-tree weights, stem weights, and volumes of planted and natural southern pines in the Southeast. Georgia For. Res. Pap. 79. Macon, GA: Research Division of the Georgia Forestry Commission. 23 p.

Johnson, F.A.; Carmean, W.H. 1953. Sampling error in the estimation of site index. Journal of Forestry. 51: 26-27.

Martin, S.W. 1998. A growth and yield model for thinned loblolly pine stands in the Georgia piedmont incorporating hardwood competition. Athens, GA: The University of Georgia. 61 p. M.S. thesis.

Wiant, H.V.; Castaneda, F. 1978. Preliminary weight yield tables for evenaged upland oak forests. West Virginia Agricultural and Forestry Experiment Station Bulletin. 20 p.

Towards an Effective Integration of Forest Inventories and Natural Resources Surveys: The Italian Perspective

Piermaria Corona and Marco Marchetti

Abstract.—International and regional efforts to define a suitable list of criteria and indicators for sustainable forest management show the new role of forestry within the environmental sector and the need for an effective integration of forest inventories in natural resources surveys. This paper examines the potential of forest inventories to support such needs, with specific reference to the Italian situation as a case study, in the enlarged framework of the European Union. In this country, where forest policy is mainly administrated at the local level, forest inventories have been on the increase since the late seventies. In spite of the many applications, a substantial sporadicalness in the adoption of inventory for forest planning and control, and a marked productive perspective can be stressed, although the high variability internal to the country in economic viability, ecological diversity, and assessment capabilities by different authorities has to be mentioned. The opportunity for simple monitoring and inventory systems focused on an overall assessment of forest attributes is devised. The field of landscape ecology can represent a common communication base to integrate the different matters in a holistic manner, solving problems in landscape planning and management. Geographic information system methodologies offer the means to operatively address this approach.

The Rio Declaration, the Forest Principles, the Helsinki-Lisbon process, and various elements of the environmentalist concept of forest quality are beginning to be used extensively in Italian forestry, in the framework of the new forest policy of the European Union (EU). The general objectives of these processes are well shared. Forest inventory and monitoring are recognized as a main focus of ecosystem management. However, their practical implementation is actually quite contradictory.

In Italy, most natural and seminatural environments are represented by forests, woodlands, and other wooded lands. On one hand, the increasing concern of people, researchers, and public administration for the values of such environments has increased the need for reliable and standardized information on forest attributes: statistics, georeferenced databases, thematic cartography, etc. On the other hand, inventories are rarely exploited for actual forest planning and control, and they are still fundamentally oriented to timber. Furthermore, to a large extent, comparable information at the national level is still missing; available data from different authorities and projects are often not homogeneous, either at national or local levels because they are developed using different measurement standards, sampling design, etc. (Corona and Ambrosini 1995, Tosi and Marchetti 1998).

Within this framework, carrying out sound forest inventory and monitoring initiatives may encourage the technical and organizational development of the whole forestry sector. Changes in land cover and in other ecosystem features have a direct impact on the social expectations about forests, especially their links with nature conservation, global climatic changes, and recreation activities. The interrelationship between forestry, nature conservation, and land planning is becoming increasingly tight in Italy, especially in the context of EU; new actions on this side have been implemented about funding, directives, and regulations.

OUTLINING THE STATE OF THE ART

Currently, the only forest information available for the whole of Europe comes from the aggregation of national data, estimated at different times and by different methods. These data are not comparable due to their typology and reliability (Köhl and Päivinen 1996). For more than 10 years, the emerging technology has been remote sensing (e.g., see the EU programs: FIRS - Forest Information from Remote Sensing, and FMERS - Forest Monitoring in Europe from Remote Sensing I&II), and the geographic information systems (GIS) integration of remote sensing (RS) techniques with existing databases. However, cartographic information for the whole of Europe is still limited to the basic classes: forests, other land (Kennedy and Folving 1997).

Associate Professor of Forest Inventory, Istituto di Assestamento e Tecnologia Forestale, Università di Firenze, Firenze, Italy, and Adjunct Professor of Forest Inventory, Facoltà di Agraria, Università di Palermo, Palermo, Italy, respectively.

A first step towards more effective coordination at the EU level has been made through the Coordinated Information on the European Environment (CORINE) program. The program has produced a Land Cover Map with three forest classes (conifers, broadleaves, mixed forests); such a map represents a common cartographic reference, suitable as an integration base for natural resource surveys. The Environmental European Agency (EEA) is now arranging the transformation of CORINE into a permanent information system.

Main EU actions are also devoted to standardizing inventory methods and proposing harmonized systems of definition and nomenclature: e.g., see the European Forest Information and Communication System (EFICS) program (EC 1997). Now near completion, a new system of nomenclature for habitat classification (EUNIS, European Information System on Nature) will integrate the older systems (CORINE Biotopes, Natura 2000, and Emerald networks, etc.), guaranteeing improved correspondence with CORINE Land Cover classification. The aim is to create a common European reference set of habitat units, with a common description and a common hierarchical classification. This will enable referencing and reporting of habitat data in a comparable manner for use in nature conservation, inventories, monitoring, and assessment; it will not replace existing national or sectoral systems except if member institutions want it to, but EEA will request that national data be based on this reference (Pinborg 1998). Indeed, the range of such initiatives clearly highlights the significant potential of EU in this perspective; the Union is becoming the main leader and reference for forest management planning processes, for inventory methods to be adopted and data to be measured at national and local levels.

Italy is one of the last European countries with only one cycle of National Forest Inventory (NFI). The Italian NFI was carried out in 1985 by systematic sampling on a 3- x 3-km grid (MAF/ ISAFA 1988). The NFI has not been repeated yet. There are some specific initiatives in the domain of land use and land cover statistics and concerning biodiversity assessment that could be connected to NFI, given their objectives and/or framework (table 1). Examples are the new "Censimento Generale dell'Agricoltura" (National Agricultural Survey), the "Carta della Natura" (Nature Map, at two scales: 1:250000/1:50000), and the "Completamento delle Conoscenze Naturalistiche di base" (Completion of the Basic Naturalistic Information, mapped at scale 1:250000). Although these initiatives are carried out by RS-based mapping (integration of Landsat TM images and digital orthophotos) and not by statistical sampling, the examined issues overlap to a large extent with the wished for repetition of NFI. Their integration would be highly fruitful, and they can be potentially devised to evolve into a global environmental inventory system. They will also benefit from an effective and prompt integration with regional forest inventory efforts.

Table 1.—*Italian forest area according to various information sources. Surfaces are expressed in square kilometers*

	NFI[1]	**Censimento Generale Agricoltura**[2]	**Annuario statistiche forestali**[3]	**CORINE Land Cover**[4]	**TBFRA**[5]
Broadleaved forests	48,090	37,283	50,174	49,021	
Conifer forests	13,320	11,055	14,362	13,096	62,810
Mixed forests	n.a.	6,768	3,558	9,746	
Other wooded land	21,609	n.a.	n.a.	25,356	30,360
TOTAL	83,019	55,106	68,094	97,219	93,170

[1] Processed NFI data. Reference year: 1985. Forest area definition: minimum crown cover equal to 20 percent, minimum area equal to 0.2 ha, minimum width equal to 20 m.

[2] Data provided by ISTAT (Italian Agency for Statistics). Reference year: 1990. Forest area definition: minimum crown cover equal to 50 percent and minimum area equal to 0.5 ha; only the forests with known owners are considered by this census.

[3] Data provided by ISTAT (Italian Agency for Statistics). Reference year: 1994. Forest area definition: minimum crown cover equal to 50 percent and minimum area equal to 0.5 ha.

[4] Coordinated Information on the European Environment, Land Cover Map. Data provided by Ministero dell'Ambiente & Centro Interregionale. Reference year: 1989 for Sicilia, Calabria, Puglia, Basilicata, Abruzzo, Molise; 1995-96 for the other Regions. Forest area and other wooded land are defined on the basis of the minimum mapping unit (= 25 ha) at the third hierarchical level of the CORINE Land Cover system of nomenclature (see: http://www.eea.dk/document/Entrecrep/Corine).

[5] Temperate and Boreal Forest Resources Assessment (EUROSTAT). Reference year: 1995. Forest area definition is that of FRA2000 classification (see: UN-ECE/FAO paper GE.97-22231, July 1997).

n.a.: not available

Within Italy, regional forest inventories have been mostly developed and optimized with respect for local needs and uses, lacking a common approach. Relevant differences in sampling design, mapping, definitions, measurement standards, filing and elaboration of the data, etc., can be highlighted. The objectives spread from timber production assessment (e.g., poplar inventories in Po valley) to forest ecosystem monitoring (e.g., inventories of the Regions Umbria and Liguria). Only a few common attributes are assessed by all the regional and the national surveys; among these, attributes directly related to wood growth and yield are still the dominant ones (table 2).

FOREST ATTRIBUTES AND INVENTORY ISSUES

Contrasting with the wood-production-oriented character of current forest inventory and monitoring procedures, an information-needs assessment carried out in the EFICS study has highlighted that, in Italy, the most expected information concerns forest health and biodiversity; data on wood production rank only third in order of importance (Tosi and Marchetti 1997).

Knowledge of forest ecosystems and the relationship with human impact is currently undergoing strong development. The quali-quantitative characterization of forests

Table 2.—*Examples of attributes currently recorded in sample plots by Italian national and regional forest inventories: NFI = National Forest Inventory; pRFI = percent of the Regional Forest Inventories that take into account the attribute. Original data are drawn from Tosi and Marchetti (1998).*

Attribute	NFI	pRFI
Land tenure	Yes	100
Site characteristics		
Aspect	Yes	100
Elevation	Yes	100
Humus type	-	9
Litter	-	9
Physiographic position	Yes	82
Slope	Yes	100
Soil depth	Yes	36
Soil structure	-	9
Soil texture	Yes	27
Stoniness	Yes	64
Ecosystem characteristics		
Animal tracks	-	9
Clearings width	-	9
Ecotones (type, shape, length)	-	9
Dead wood	-	9
Shrub abundance and distribution	-	9
Vegetation (phytosociologic survey)	-	9
Stand structure		
Coverage percent	Yes	82
Dominant trees age	-	9
Height and spatial tree distribution	-	45
Plantation spacing	Yes	9
Stand age	Yes	100
Silvicultural characteristics		
Forest type	Yes	100
Silvicultural system	Yes	82
Tending practices	Yes	18
Regeneration		
Abundance	Yes	45
Distribution	Yes	36
Gamic/agamic origin	Yes	9
Health	Yes	36
Prevailing species	Yes	45
Forest health		
Damaged stems	Yes	18
Defoliation	-	9
Foliage decoloration	-	9
Site damages	Yes	9
Tree attributes		
Bark thickness	-	27
BH increment	Yes	45
Cork (quality, thickness, size)	Yes	9
Crown size and shape	-	45
DBH	Yes	100
Social position	-	45
Species	Yes	100
Stem quality	Yes	55
Stump diameter	Yes	27
Total height	Yes	100
Upper-stem diameters	-	45
Harvesting potential		
Accessibility	Yes	82
Distance from the nearest road	Yes	18
Road density	-	55
Rocky outcrops	-	27
Roughness	Yes	36
Under-cover density	-	27

has been theoretically extended, focusing on their values as complex and multifunctional systems in an integrated way: wildlife habitat, soil erosion control, nature conservation, aestethic values, recreation, etc. The opportunity for simple monitoring and inventory systems focused on an overall assessment of forest attributes has been devised (Corona and Ambrosini 1995; see also table 3).

However, the current level of actual knowledge is still unsatisfactory for several reasons and for several aspects. Even the total area of forests actively managed is still not well recognized in Italy. Comparing the data from Censimento Generale dell'Agricoltura with CORINE Land Cover leaves at least 1.2 million ha of forests with unknown owner (table 1). The impact of such a problem cannot be actually quantified; nonetheless, it cannot be neglected from an environmental and socioeconomic point of view (Bianchi *et al.* 1998).

Forest fires represent another main aspect for which data are still not available on a permanent statistical inventory basis. Specific research initiatives on such a topic are in progress at the EU level; see Reg. 2158/92/EU and followings, DOBRIS 3+, and other research programs on fire risk assessment, management, and monitoring of burnt-over areas using RS techniques (e.g., Megafires, Fuego, Skymed).

Table 3.—*Selected miscellaneous examples of indicators to be monitored at management unit/landscape levels within a multiple-use forestry context*

Age structure within stands
Amount of big trees
Amount of strictly protected forest area
Amount of old-growth forest areas
Amount of undisturbed forest areas
Amount of other forest areas with special ecological values (e.g., wet biotopes)
Dynamic series of vegetation
Forest fragmentation (e.g., fractal dimension, contagion, and interspersion of forest cover: see also table 6)
Implementation level of forest management planning
Local community participation in forest management planning
Net increase in forest area
Non-wood goods
Number of shrub species
Number of tree species
Standing dead wood

A high impact on Italian forest accounting will be exerted by the new forest area definitions introduced by FAO Global Forest Resources Assessment (FRA2000) implying that future surveys will be routinely extended to cover woodland with forest crown cover of more than 10 percent and the so-called "other wooded land" (forest crown cover between 5 and 10 percent). It is essential that forest inventory domain extends outside woodlands; in Italy, this class includes many natural and seminatural environments, neighboring, and often dynamically connected to, the forests, with a fundamental ecological value (e.g., abandoned agricultural land, the areas above the timberline, etc.). The only current examples of inventories concerning "other wooded land" are the "abandoned agricultural land" surveys to assess reforestation suitability, e.g., see the forest inventories of Umbria Region, of the Park of the Simbruini Mountains, and of the Comunità Montana Alto Lazio.

An increasing impact on forest inventory and monitoring is also expected by the EU Habitat Directive (Dir. 43/92/EU) aimed at creating an European network of nature conservation sites. The directive requires the description of forests and other natural and seminatural habitats following a common system of nomenclature (the EUNIS system in the near future). After the designation of a site to be protected, the directive also imposes management planning and monitoring, posing the problem of assessing habitat and ecosystem changes with respect to biodiversity conservation. There are many procedures to measure diversity in a scientific sense, but it is doubtful if these procedures are suited to assess the specific features of forest biodiversity (Corona and Pignatti 1996). Quantitative and qualitative data on different factors are recognized as indicators, but because what they mean for biodiversity in forest landscapes is not truly understood, their monitoring could be ineffective. Even the question of how to assess the effects of forest management on biodiversity is complicated by the complexity of forest ecosystem relationships with human impact; there is little actual evidence of the effectiveness of improved forest management in preserving biodiversity even in relatively simple temperate systems (Mooney *et al.* 1996). Studies on forest biodiversity indicators are currently being carried out at the EU level; see concerted actions like Forest Biodiversity Evaluation (BEAR) and proposed shared-cost programs like Biodiversity Evaluation Tools for National Forest Inventories (NFIBET).

THE POSSIBLE CONNECTING ROLE OF LANDSCAPE ECOLOGY

One of the most fundamental considerations for the development of inventory and monitoring methods is the need to consider forest ecosystem as a whole. From an operational point of view, such an approach implies wise use of RS and GIS techniques enabling a global view of the forest in the landscape, including borders, clearings, open woodland, etc. From a methodological point of view, the landscape ecology approach can provide a suitable basis for a common communication framework to integrate all different facets in a holistic perspective.

The forest landscape can be seen as a mosaic of individual parcels/patches of different land cover types. Landscape structure is largely determined by the origin, number, and size of the patches. Bailey *et al.* (1978) state that "the relationship between components of landscape and physical and biological processes is almost always through spatial pattern rather than through composition alone " Therefore, a natural way to describe and compare landscape structure is by measuring the shape and configuration of patches within a landscape, or other spatial attributes, using RS and GIS techniques.

Landscape ecology perspective is strongly appreciated in Europe. For instance, the EUNIS habitat classification system is based on general vegetation science with landscape elements to identify habitats. A synthetic comparison between land system and phytosociologic approaches is outlined in table 4. A comparison of the hierarchic levels among some widespread "typification-classification" approaches used in landscape ecology surveys is shown in table 5.

Table 4.—*Comparing land system and phytosociologic approaches, according to Blasi* et al. *(1998)*

Land system approach	Phytosociologic approach
Hierarchic system for for typification	Hierarchic system classification
Holistic	Synthetic
Always mapped	Independent of the presence of maps

In the light of the suggested perspective, landscape ecology could be a sound way to integrate forest in land analysis, and forest inventories can take the broader meaning and value of integrated systems of territorial analysis, at least concerning the main component of natural renewable resources. For instance, spatial/texture features can be used to quantify the degree of homogeneity/heterogeneity of the landscape (Corona and Ferrara 1998, Marchetti 1996). Fragmentation of the forest area can be characterized using some simple metrics of landscape, such as area of the biotopes, their density, size, and variability. In addition, edges, shape of the biotopes, core areas, and nearest neighbors can also be used as indicators of landscape diversity. There is also a group of diversity indices traditionally used in assessing species diversity that can be used to determine landscape homogeneity/heterogeneity (table 6).

In Italy, some national databases organized on GIS's, like the digital terrain model and the land cover data of CORINE, could be properly integrated with data collected through forest inventories, from a landscape ecology perspective. At the regional level, the forest inventory of Liguria Region may represent a prototype for the integration in the Forest GIS of different analyses and modules; its main themes have concerned the status of forest ecosystems (evolution processes, decline symptoms, and fires), their spatial distribution in the landscape, and the multiple functions supported at local and regional levels (Marchetti *et al.* 1998).

FURTHER TOPICS

Final remarks towards an effective integration of forest inventories and natural resources surveys have to take into account the benefits from emerging technologies and the role of inventory systems connected to forest management planning and certification systems.

1. Given the increasing capability and potential of RS techniques (Corona and Ferrara 1998), it is even more essential to define nomenclature systems and statistical approaches that allow effective integration of RS mapping and ground sampling surveys; direct and derived forest and land-use attributes could be

Table 5.—*Hierarchic levels in some typification-classification approaches used in landscape ecology surveys (for details and bibliographic references, see Blasi* et al. *1998)*

CSIRO	ITC – Wageningen	Dent & Young	Phytosociologic approach
	Ecotope or site	Land element	Tessera
Land units	Land facet	Land unit/land facet	Catena
Land systems	Land system	Land system	Catena
	Main landscape	Main landscape	

Table 6.—*Examples of available indicators for assessing biodiversity by remote sensing (modified from Marchetti 1996). The features derived from the co-occurance matrix or geometrical structure of the group of segments could serve as the basis for a method to quantify and monitor the biodiversity of a landscape, and to compare the biodiversity of different landscapes. In addition to RS material, available ground truth data and other auxiliary data can be used.*

Indicators measurable from RS images or auxiliary data	Indicators of biodiversity when ground truth data are available
Image features - Haralick's texture - Fragmentation indexes * Area * Biotope density, size and variability * Biotope richness * Biotope richness density * Contagion and interspersion * Core area * Edge * Modified Simpson's diversity index * Modified Simpsons's evenness index * Nearest neighbor * Relative biotope richness * Shannon's diversity index * Shape Shannon's evenness index * Simpson's diversity index * Simpsons's evenness index - .... *Territorial auxiliary data* - Minor biotopes (e.g., springs, streams network) - Topography (DEM) -	- Amount of forest of natural origin (e.g., as defined by EU DOBRIS+3) - Amount of old-growth forests (e.g., as defined by EEA, World Wildlife Fund, etc.) - Designated conservation/recreation areas - Forest reserves (e.g., see EU COST E4, 1997) - Key biotopes (e.g., EU Natura 2000 sites) (types, number, size, interspersion, rarity, etc.) - Habitat description (e.g., as defined by EU EUNIS physiognomic classification) - .....

assessed in the near future using high resolution imagery even at a local scale.

2. To effectively insert sustainable forestry issues into land planning, it is necessary to define inventory categories suitable to join cartographic and ground sampling efficiency with planning requirements and constraints. An interesting proper way out, useful also from a silvicultural point of view, may be found by structurally linking inventory categories (and strata) to forest typologies now being developed by many Italian Regions (e.g., Veneto, Liguria, Toscana, Piemonte, Lazio and Valle d'Aosta).

3. Most international political initiatives and their followups are making forest inventory and monitoring more and more crucial from a legally binding point of view. Forest inventories have to translate the meaning and the purposes of issues such as biodiversity conservation, forest management sustainability, etc., to actual figures and facts. A relevant example is the Kyoto legally binding protocol that explicitly refers to forest inventory data for assessing greenhouse gases emission/uptake balance at global and national levels.

4. A similar issue concerns forest ecocertification, which is being developed all over the world. As stressed by Lund (1998), "forest inventory designers and managers must familiarize themselves with the requirements for certification and work with the landowners and managers to ensure that the inventories and monitoring systems employed will yield the desired information at the least cost." For the EU countries, the Helsinki-Lisbon process (1994, 1998), which is refining criteria and indicators for sustainable forestry, represents a steady reference point (Parviainen and Paivinen 1998). The list of the most important forest attributes that have been collected during the EFICS study fits well with the criteria and indicators developed in that process. Twenty-seven significant indicators have been identified to assess

the sustainability of forest management at national level. In Italy, only a few of these can be currently obtained from the available inventory data. Adequate priorities then have to be set.

ACKNOWLEDGMENTS

The work, carried out with equal contributions by the authors, was partially supported by the Italian National Council of Research (CNR) under the Project "Procedure innovative per la classificazione di tipologie forestali tramite analisi delle relazioni spaziali rilevate con immagini da satellite" (project leader: P. Corona).

The following people reviewed this manuscript: Dr. Marco Albani, Forest Science, University of British Columbia, Vancouver, Canada, and Dr. Roberto Scotti, Istituto di Assestamento e Tecnologia Forestale, Università di Firenze, Italy.

LITERATURE CITED

Bailey, R.G.; Pfister, R.D.; Henderson, J.A. 1978. Nature of land and resource classification: a review. Journal of Forestry. 76: 650-655.

Bianchi, M.; Corona, P.; Marchetti, M. 1998. Gli inventari e il controllo dei sistemi forestali italiani. In: Atti, Secondo Congresso Nazionale di Selvicoltura, Venezia. Italy. 1998 June 24-29 (in press).

Blasi, C.; Carranza, L.; Marchetti, M. 1998. Landscape ecology: comparison of various different approaches and methodologies. International Journal of Environmental Design. 1 (in press).

Corona, P.; Ambrosini, I. 1995. Inventari forestali in Italia. L'Italia Forestale e Montana. 2: 198-214.

Corona, P.; Pignatti, G. 1996. Assessing and comparing forest plantations proximity to natural conditions. Journal of Sustainable Forestry. 4: 37-46.

Corona, P.; Ferrara, A. 1998. Orientamenti tecnici innovativi nell'inventariazione e monitoraggio dei sistemi forestali. In: Atti, Convegno 'Nuove frontiere della gestione forestale', 1997 May 30-31, Reggio Calabria. Italy. Accademia Italiana di Scienze Forestali, Firenze (in press).

EC 1997. Study on European forestry information and communication system. Reports on forestry inventory and survey systems (Vol. 1, 2). Official Publications of the European Communities, Luxembourg. 1,328 p.

Kennedy, P.; Folving, S. 1997. FIRS status report. October 1997. Ispra. Italy: Space Applications Institute, Env. Mapping and Monitoring. 24 p.

Köhl, M.; Päivinen, R., eds. 1996. Definition of a system of nomenclature for mapping European forests and for compiling a Pan-european Forest Information System. Space Application Institute, CCR, European Forest Institute, WSL-FNP. Luxembourg. EUR 16416: 238 p.

Lund, G. 1998. Guest editorial. IUFRO4.02/11/12 Newsletter. 23, 3 p.

MAF/ISAFA 1988. Inventario Forestale Nazionale. Sintesi metodologica e risultati. Ministero dell'Agricoltura e delle Foreste. Istituto Sperimentale per l'Assestamento forestale e per l'Alpicoltura. Trento. 364 p.

Marchetti, M. 1996. Analisi spaziale di dati telerilevati per la valutazione della diversità nei paesaggi forestali. Atti, 1° Congresso IAED, Perugia. Italy. Quaderno IAED. 6: 71-78.

Marchetti, M.; Campaiola, F.; Lozupone, G.; Tosi, V. 1998. Forest clearings, margins and mixed area survey for diversity assessment in the Ligurian Inventory (Northern Italy). In: Proceedings, Assessment of biodiversity for improved forest planning. Kluwer Academic Publishers. EFI Proceedings. 18: 291-300.

Mooney, H.; Cushman H. J.; Medina, E.; Sala, O.E.; Schulze E.D., eds. 1996. Functioning role of biodiversity: a global perspective. New York, NY: John Wiley & Sons.

Parviainen, J.; Paivinen, R. 1998. Information needs for biodiversity assessment derived from international forestry discussion. In: Proceedings, Assessment of biodiversity for improved forest planning. Kluwer Academic Publishers. EFI Proceedings. 18: 63-70.

Pinborg, U. 1998. Development of the EEA EUNIS habitat classification. EU Draft Report, 17 March 98, Brussels, Belgium.

Tosi V., Marchetti M., 1997. Country report for Italy. In: Study on European forestry information and communication system. Reports on forest inventory and survey systems. Volume 1. CH-11-97-001-EN-C. European Commission. Luxembourg: 423-646.

Tosi, V.; Marchetti, M. 1998. I sistemi informativi forestali in Italia: uniformità e divergenze negli inventari delle risorse forestali. L'Italia Forestale e Montana. 4 (in press).

State-of-the-art Technologies of Forest Inventory and Monitoring in Taiwan

Fong-Long Feng

Abstract.—Ground surveys, remote sensing (RS), global positioning systems (GPS), geographic information systems (GIS), and permanent sampling plots (PSP) were used to inventory and monitor forests in the development of an ecosystem management plan for the island of Taiwan. While the entire island has been surveyed, this study concentrates on the Hui-Sun and Hsin-Hua Experimental Stations of Chung Hsing University and the Northeast Coast National Scenic Area. The 7,500-ha Hui-Sun Experimental Station is located in the middle part of Taiwan, the 550-ha Hsin-Hua Forest Experimental Station is in the southern part of the island, and the 9,450-ha Northeast Coast National Scenic Area is in the northern part. GIS land-use maps derived from the aerial photographs of RS were used to select and survey PSP to obtain information about forest stand structure and growing stock. This information on the landscape patterns and changes of land use was used in the Hui-Sun Experiment Forest Station to detect changes in trends. The georeferenced surveyed data from the PSP were used to update forest attributes in GIS at different scales: landscape, forest stand, and tree. A tree location map was developed using compass, laser, and GPS techniques within each PSP. The georeferenced database allowed for the examination of the relationship between different species and their habitat. Research is ongoing. The problem of resource surveys and environmental monitoring at large scales and over the long term is also being studied.

Long-term forest management has two objectives: forest utilization and resource conservation. The problem most forest managers face is that of accessing the information to make necessary decisions. By integrating existing databases with well-designed forest inventories and monitoring systems, it is possible to focus attention on the indicators and criteria needed for forest ecosystem management planning and for forest policymaking. A forest inventory is one that obtains information about forest resources: the quality and quantity of the resources and the local land area characteristics (Husch *et al.* 1982). Forest monitoring involves evaluating the data collected in a forest inventory for estimating baseline conditions and for implementing management objectives (Haynes *et al.* 1996). The main focuses of ecosystem management (EM) are maintaining forest health, sustaining and restoring diversity, and restoring long-term productivity. Bioecological and social-economical criteria, however, also need to be considered. In Taiwan, there have been three forest inventories: in 1954, 1977, and 1994. The results of these inventories have been correlated with base maps, ground survey plots, aerial photos, and forest management records to produce land-use map digital terrain models (DTM) and area and volume of each working circle. These have all been linked in geographic information systems (GIS).

Since it was developed in the 1960's, GIS technology has been widely used for ecosystem management (EM). GIS can be used to integrate map layers and attribute data derived from remote sensing (RS), data logging, computer mapping, database management, and geographic spatial analysis. This integration allows for the estimation of information and the evaluation of survey sampling design in various forest inventories and monitoring systems. The spatial statistical analysis capacities of GIS allow for site analyses, community analyses, planting species selection, density control, and land classification. The recent development of global positioning systems (GPS) and laser surveyors, has increased the ability to do forest ecosystem surveys and measurement integration. The more recent creation of permanent sampling plots (PSP) and adaptive management areas has been very important for conducting continuous forest inventories and for developing monitoring systems for EM. The data and information surveyed from these areas make it possible to compare natural and artificial aspects of management. In developing land information systems for EM and forest research, use of RS, GIS, GPS, and PSP is vital.

With the continued improvement and integration of remote sensing, GIS, and GPS technologies, their utility for forest inventories and EM monitoring systems will also increase. Remote sensing combined with PSP ground surveys will allow for updating existing databases and for monitoring the status, function, and change in the characteristics of a multiscale forest ecosystem. GIS makes this integration possible by improving accuracy in

---

Professor, Department of Forestry, National Chung Hsing University, 250 Kuo Kuang Road, Taichung, Taiwan, Republic Of China.

classification and estimation. It also provides effective cartographic control, and enables PSP to be located within the databases efficiently and accurately.

Ground surveys and RS (aerial photography, satellite imagery, etc.) are used to create and update an information database. Location is a very important factor in natural resource management and environmental monitoring, and GPS is a useful technology to determine the coordinates of a particular location. GIS is a versatile tool for storing, retrieving, processing, and analyzing the spatial distribution of significant properties of the earth's surface. PSP are created for the evaluation and adaptation of forest inventories and research, and for ground truth data collection.

The purpose of this paper is to demonstrate the use of state-of-the-art technology in the forest inventory and monitoring systems of Taiwan. Remote sensing, GIS, GPS, and PSP technologies are used in the development of sampling design, surveys, data management, and analysis of the forest inventory and forest monitoring system for EM in Taiwan. A flow chart of the forest inventory and monitoring system for EM in Taiwan is shown in figure 1.

STUDY AREA

Taiwan is a mountainous island of 3,598,000 ha off the southeast coast of Mainland China and north of the Philippines (fig. 2). The Central Mountain Range runs north-south down the center of the island and reaches elevations over 3,900 m. Three land-use surveys and forest inventories have been performed in Taiwan: from 1954 to 1956, 1972 to 1977, and 1989 to 1993. The Hui-Sun Experiment Forest Station is located in the

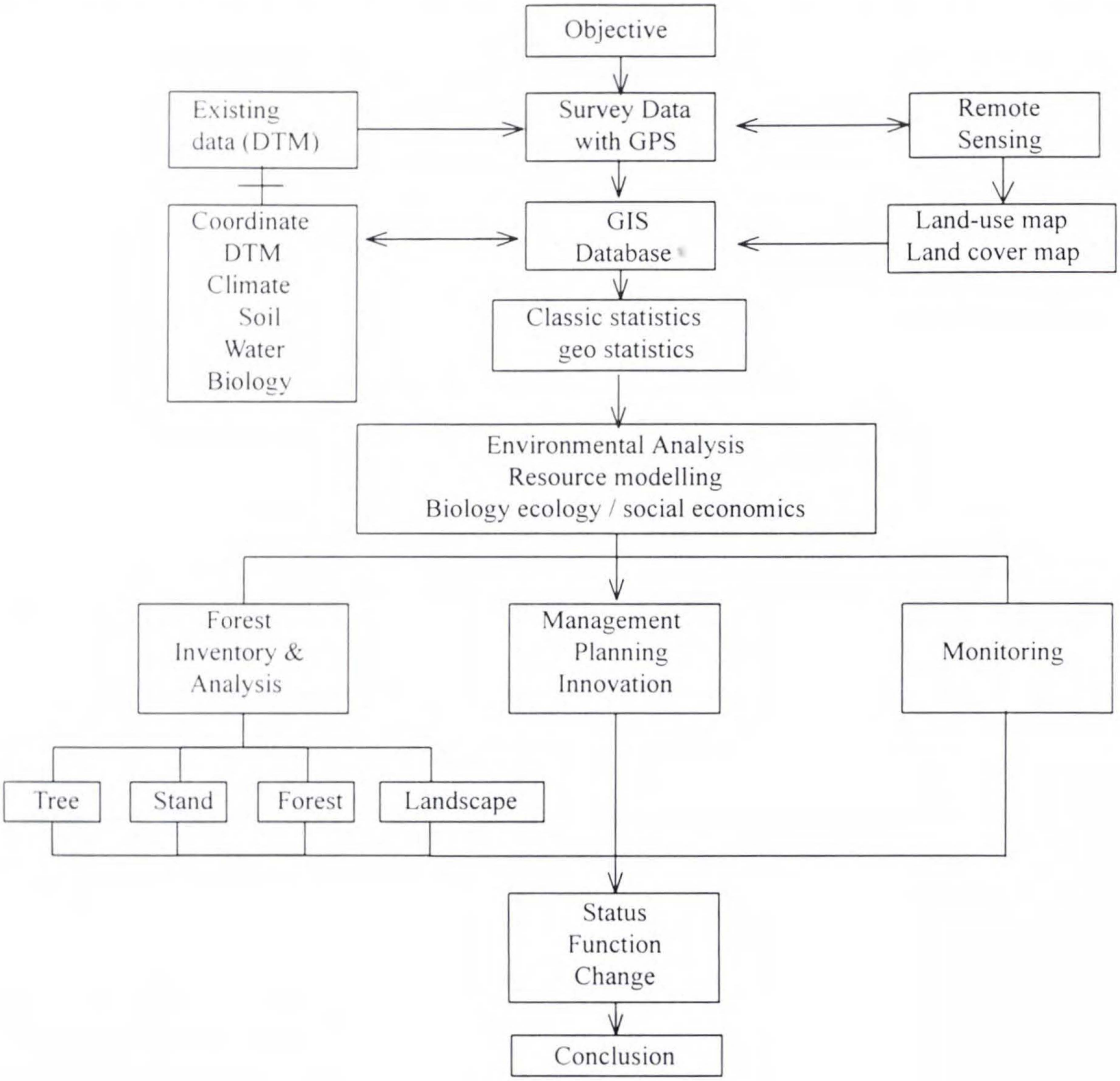

Objective
Existing data (DTM)
Survey Data with GPS
Remote Sensing
Coordinate
DTM
Climate
Soil
Water
Biology
GIS Database
Land-use map
Land cover map
Classic statistics
geo statistics
Environmental Analysis
Resource modelling
Biology ecology / social economics
Forest Inventory & Analysis
Management
Planning
Innovation
Monitoring
Tree
Stand
Forest
Landscape
Status
Function
Change
Conclusion

Figure 1.—*Integrating RS/GIS/GPS/PSP in forest inventory and monitoring.*

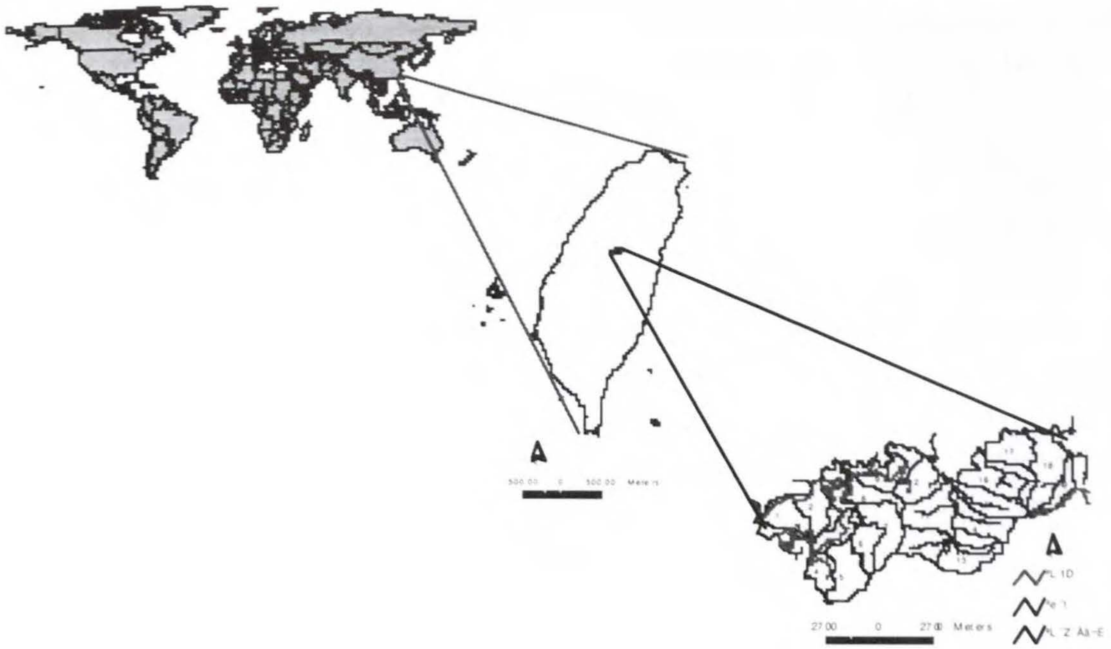


Figure 2.—*The location of compartments and rivers in Hui-Sun Experiment Forest Station.*

Beikangshi watershed in Nantou County in the central part of Taiwan (fig. 2). The station (7,600 ha) contains 19 forest compartments and 4 rivers. The elevation ranges from 550 m to 2,400 m. As a result of Taiwan's third forest inventory and land-use survey, there are several monitoring experiments in the station, including the Son-fen Mountain Area and a 400-ha Long-Term Ecological Research (LTER) site. This LTER site contains seed production gardens of *Schima superba* and *Calocedrus formosana*. Within the LTER site are many field studies of forest vegetation, biomass, productivity, parasitic plants, mammals, birds, insects, hydrochemicals, nutrient cycling, and meteorology. The Hsin-Hua Forest Station (fig. 3) is located in the southern part of Taiwan. It has 550 ha, of which 173 ha are privately owned, and it is made up of 10 forest compartments. The conservation of soil and water is the main function of this station. There are 62 permanent sampling plots set up within the station to monitor tree growth and yield. Fifty percent of the forest station is covered with a *Sweitania microphylla* plantation. The Northeast Coast National Scenic Area is located on the northeast coast of Taiwan: 9,450 ha of terrestrial area and 4,275 ha of sea area for a total of 13,725 ha. This is handled by the Taiwan Tourism Bureau.

MATERIALS

Digital Terrain Model

The Agricultural and Forestry Aerial Survey Team of the Taiwan Forestry Bureau made a DTM of Taiwan from control points and orthophoto models of Taiwan at the scale of 1:5,000 40 m x 40 m scale in 1981.

Temperature Data

The average temperature, tetratherm, maximum temperature and minimum temperature were derived from the long-term data sets of 26 meteorological stations distributed throughout Taiwan.

Precipitation Data

The average summer and autumn precipitation data were collected from 818 long-term stations, which include the 26 meteorological stations mentioned above.

Soil Data

The data on soil type, texture, and depth were determined from 3 km x 3 km systematical soil profile spots over 1,000 m in elevation. The spots had been surveyed in the third forest inventory and land-use survey of Taiwan.

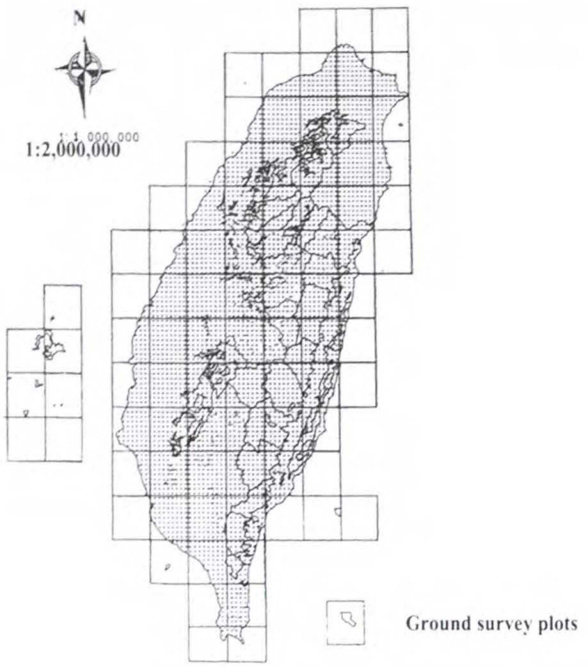


Figure 3.—*Location of Taiwan Forestry Bureau compartments and areas of private ownership within the Hsin-Hua Experimental Forest Station.*

Forest and Land-use Data

The entire island was surveyed using aerial photographs from 1987, old-base maps and aerial photographs, and ground survey plots systematically sampled in 1989-1993. The ground survey plots were selected from a 3-km x 3-km grid starting with the Chiang-Kai-Shek Memorial Hall in Taipei (Feng 1996). The resulting 4,002 ground survey plots are shown in figure 4. These plots were found to contain 66,979 individual trees (excluding supplemental plots containing 56,267 trees) (Feng 1996).

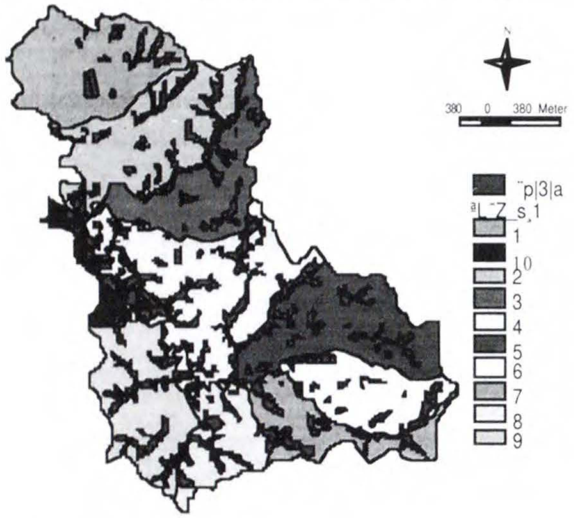


Figure 4.—*The location of the ground survey plots and working circles of the third forest inventory of Taiwan (1989-1993).*

METHODS

Data were collected from aerial photographs taken 1,200 ft above ground level and from ground survey plots (fig. 4). Spreadsheet and database management systems were used to input attribute data. A digitizer, scanner, and GIS software were used to input map data. Data were stored on rewritable 640 MB, 540 MB disks, CD disks, and 2 GB, 4GB, and 8 GM hard disks in formats suitable for use with Arc/Info and Arc/View. The SAS statistical package was used for analysis and development of mathematical models of the attribute data. Imagine was used for image processing. The functions of Arc/View used for spatial analysis were Overlay, IDW, Trend, Kriging, Spline of interpolation, spatial modules, and network modules.

RESULTS AND DISCUSSION

Multiscale and integration concepts were used in Taiwan's forest inventory and monitoring system. The scales used were island (Taiwan), region (working circles, Hui-Sun Experimental Station, Hsin-Hua Experimental Station, Northeast Coast National Scenic Area), landscape (land-use types, land cover), stand (Chinese cypress plantation, mahogany plantation, temperate natural community), plot, and individual tree. An environmental database was created to integrate the data of different areas of research.

Airborne Data Acquisition and Management System

The availability of frequent, relatively low-cost, and safe opportunities using sensors of different scales from a remote control aircraft platform to observe the earth's surface for environmental monitoring or other environmental experiments has become an essential component of today's remote sensing technique. A system like this not only provides valuable scientific data leading to new discoveries, it also allows for the acquisition of vital preliminary information for larger mission planning. A portable airborne data acquisition and management system (ADAMS) based on this concept is being developed in cooperation with the Department of Bioresource Engineering of Oregon State University. The goal is to integrate multiple remote sensors, spectral measurement devices, GIS, and GPS for automated airborne and field data acquisition and for near real-time data environmental analysis capability (Chen and Feng 1995). In the future, the expectation is for ADAMS to be used in remote control aircraft for forest inventory and monitoring at several low elevation scales.

Global Positioning Systems

GPS was developed to collect spatial data (coordinates and altitudes on the earth's surface) that can be put into GIS for storage and analysis. In a forest inventory, it is generally difficult to accurately position ground permanent plots from aerial photos. Ground surveys using differential GPS were made to determine the position of permanent plots in the Song-Fen Mountain Area of the Hui-Sun Experimental Station. GIS was then used to label the coordinate data. The results of this method showed that the coordinate data of base stations were congruous to the national standard of first class trilateration (Feng and Huang 1994). By using differential GPS, permanent plots, forest roads, and planting areas could be positioned accurately (Feng and Huang 1996). By putting the coordinate data into GIS, the spatial and attribute data of the permanent plots and areas of interest could be easily linked.

Sampling Design for PSP

The spatial analysis techniques of GIS are used to study the sampling allocation and sample-plot building of the Hsin-Hua Experiment Forest Station. In sample-plot building, buffer analyses of GIS were used to study the minimal sampling area with variance method, running mean method, diameter distribution method, and diversity method. Simulation was used to determine the numbers of unequal probabilities sampling with programming and GIS.

The Third Forest Inventory in Taiwan

For Taiwan's third forest inventory, remote sensing data of the entire island were used to detect changes over time from maps of land-use type, crown closure, and growing-stock classes. Combined with previous inventories, this inventory showed significant changes in forest area, increasing from 1,680,000 ha in 1977 to 2,100,000 ha in 1993. Currently, about 58 percent of Taiwan is covered with forest (Taiwan Forest Bureau 1994). The growing stock has been stable at about 170 m^3/ha.

This GIS analysis of Taiwan's economic forests was used to create a database for use in timber management. The database includes the position and physical condition of the forests, species composition, stand structure, stand development, and growing stock (Feng 1996). From this information, it is possible to develop a timber management strategy for Taiwan, and to consider several small scales as well as derive information at larger scales. In Taiwan, spatial and temporal factors of natural resources were used to integrate the survey data from different surveys and inventories of different scales.

A multiscale spatial database management system is being tested at the Guandashi Long Term Ecological Research (LTER) site in the Hwei-Sun Experimental Station (fig. 2). Current work focuses on aggregating and integrating the data of different spatial levels; developing a uniform input format for the database and DBMS; integrating the data from different surveys of different spatial scales; analyzing for information on status, function, and change; and sharing the data via the Internet and e-mail.

Spatial Interpolation

Maps of Taiwan summarizing the weather conditions (temperature and precipitation) were made by interpolating data from the meteorological stations (Kao and Feng 1998). Soil type and land use maps were made by interpreting the data collected from ground-survey plots in the third forest inventory (Taiwan Forest Bureau 1994). These data were also used to estimate average annual precipitation, temperature, and transpiration. Application of the Holdridge model of ecoregion classification to Taiwan resulted in categorizing Taiwan's habitats as belonging to the rainforest and moisture forest zones. This classification when combined with analysis of species composition within each zone will allow for the modeling of effects of climatic change within the island (Feng 1996).

Examples of Multiscale Analysis

In the Hui-Sun Experimental Station, aerial photographs and data from Taiwan's first, second, and third forest inventories (Feng and Huang 1996) were combined to produce topographical land-use maps. In addition, a detailed study on the growth rates of China fir (*Cunninghamnia lanceolata*) in plantations with various thinning treatments was also made (Feng 1997). The results of these analyses showed that the type and diversity of forest stands have changed over the past 30 years with a trend towards increasing complexity and diversity as native broadleaf species invade the plantations of China fir. Furthermore, the thinning experiments demonstrated that China fir grows most efficiently at very high thinning rates. Thinning rates of 60 percent, however, leave light gaps in the stand that may encourage invasions by native broadleaf species. Current work is studying the invasion rates by broadleaf species and the effect of different-size light gaps.

In the Northeast Coastal National Scenic Area, a similar study was conducted (Feng and Huang 1997a). In this area, land use over the past 30 years has also changed, but not because of natural invasions by native species. In this case, the change has come from increased human activity: building and the creation of plantations. As this trend has been identified, current studies are examining the effect these changes may have on the area.

In the Shin-Hwa Experimental Station, studies have focused on evaluating tree growth rate, growing-stock volume, and structure in stands of *Swietenia macrophylla*. Studies such as this and the China fir study in the Hui-Sun Experimental Station are necessary. These studies collect information on growing stock and volume, on forest cover, on changes in land use over time, and on changes in biomass from year to year that will be useful in evaluating carbon sequestration and emission in Taiwan's forests. Studies of this sort are of increasing importance as high levels of carbon in the atmosphere are being identified as a cause of global warming (Chen *et al.* 1997).

An Example of Integration

In the Northeast Coast National Scenic Area, GIS is being used to integrate vegetation data from permanent plots and a moth-trap inventory of local insects. From 9 months' trapping in 1995, a total of 1,790 individuals representing 19 families and 144 species of insects were collected. This study identified the summer months as the most active season for insects, and it identified the most common species in the area (Feng *et al.* 1998a, b). Current work is focusing on collecting the microhabitat data and correlating this with environmental trends and the observed insect diversity and frequency. The goal is to gain enough understanding of the system to provide some focus for long-term monitoring. There is also a strong interest in correlating each species with a host plant.

In the Hui-Sun Experimental Station, many different research projects are being done at the Guandashi LTER site (Feng 1997). From the GIS analysis described above involving scales at the levels from station land-use categories to individual tree growth rates, the conclusion was that collecting data at the level of the individual tree had the most utility. Currently, all the data collection for the different research projects at the LTER site is encouraged to be at the level of individual trees (Feng *et al.* 1998a). If this is successfully managed, then the data from studies of amphibians, parasitic plants, small mammals, and habitat can be integrated into GIS for a more comprehensive picture of the forces at work at this LTER site.

Forest Ecosystem Management

Studies such as the ones outlined here that inventory and analyze the forests of Taiwan are needed for forest management. These studies have concentrated on the forest stand types and the natural and human activities that occur within each stand. In the Hsin-Hua Experimental Station, analysis has also included maps of water systems, transportation systems, and land ownership and administration (Feng and Tsai 1998). Combining forest inventory data with maps of human activity within and around the forest is necessary to better model the changes that are occurring.

Forest ecosystem management (EM) must begin by considering the never-ending demand of human beings for goods and service and the limits of biological and ecological resources. With the limited knowledge and techniques currently available, the problem is determining how to manage a forest. To resolve this problem, it is necessary to integrate the knowledge, interests, and demands of the public, scientists, and forest managers. Before integration can be done, however, criteria for sustainable management at different landscape scales must first be created. Once the criteria have been decided upon, data can be collected from ground survey of permanent plots, remote sensing, photogrammetry, GPS, and social surveys for integration into GIS for spatial, non-spatial, and temporal analysis. In Taiwan, "managerial experiments" have been designed using biological, ecological, sociologi~~cal, and economi~~cal knowledge and techniques to develop an adaptive management system. Models of different forest scenarios have been used to plan ideal forests for the future. To develop these "managerial experiments" and forest scenario models, the criteria and index of EM monitoring had to be measured and evaluated first. With the results of EM monitoring, it is possible to develop and improve the practice and procedure of forest ecosystem management in Taiwan.

LITERATURE CITED

Chen, Chaur-Fong; Feng, Fong-Long. 1995. Airborne data acquisition and management system. Remote Sensing. 22: 39-52.

Chen, Chih-Sheng; Chen, Ying-Yuan; Feng, Fong-Long; Huang, Chin-Cheng; Lin, Ming-Jing; Lin, Tzu-Yuh. 1997. Practicing secondary forest inventory and developing geographical database in Hsin-Hua Forest Experiment Station. Journal of the Experimental Forest of National Chung Hsing University. 19(1): 1-21.

Feng, Fong-Long. 1996. GIS model-based spatial analysis of forest stand structure and volume estimation. Journal of the Experimental Forest of National Chung Hsing University. 18(2): 80-97.

Feng, Fong-Long. 1997. Modelling stand growth varies in response to different spacing. Quarterly Journal of Experimental Forest of National Taiwan University. 11(2): 111-123.

Feng, Fong-Long; Huang, Chin-Cheng. 1994. Global positioning system used in permanent plot positioning. Quarterly Journal of Chinese Forestry. 27(2): 69-86.

Feng, Fong-Long; Huang, Chin-Cheng. 1996. Integration of GIS and GPS techniques in forest mapping. Journal of the Experimental Forest of National Chung Hsing University. 18(1): 137-150.

Feng, Fong-Long; Huang, Chin-Cheng. 1997a. Landscape pattern and changes of land use in Hui-Sun Experimental Forest Station. Quarterly Journal of Chinese Forestry. 30(4): 387-400.

Feng, Fong-Long; Huang, Chin-Cheng. 1997b. The study of parameters of stand structure by using the spatial interpolation model. Journal of the Experimental Forest of National Chung Hsing University. 19(2): 57-76.

Feng, Fong-Long; Tsai, Jeng-Horng. 1998. Application of GIS techniques for forest sampling design. Journal of the Experimental Forest of National Chung Hsing University. 20(1): 81-99.

Feng, Fong-Long; Tsai, Shung-Der; Yang, Jeng-Tze. 1998a. Vegetation and insect survey of the Northeast Coast National Scenic Area illustrating integrated forest resource inventory and monitoring. Journal of Agriculture and Forestry. (in press).

Feng, Fong-Long; Tsai, Shung-Der; Yang, Jeng-Tze. 1998b. Study of the insect resource inventory and monitoring using moth trap in the Northeast Coast National Scenic Area. (in press)

Haynes, R.W.; Graham, R.T.; Quigley, T.M. 1996. A framework for ecosystem management in the interior Columbia Basin and portions of the Klamath and Great Basins. Gen. Tech. Rep. PNW-374. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 67 p.

Husch, B.; Miller, C.I.; Beers, T.W. 1982. Forest mensuration. 3rd ed. New York: John Wiley & Sons. 402 p.

Kao, Jian-Tai; Feng, Fong-Long. 1998. Spatial interpolating the factors & clusters of forest habitat. In: Proceedings of the 17th survey academic and application conference; 1998 September 7-9. Taiwan: National Cheng-Kung University, Taiwan Republic of China.

Taiwan Forest Bureau. 1994. The third forest resources and land use inventory in Taiwan. Taiwan: Taiwan Forest Bureau, Department of Agriculture. 257 p. (In Chinese.)

History of Forest Survey Sampling Designs in the United States

W.E. Frayer and George M. Furnival

Abstract.—Extensive forest inventories of forested lands in the United States were begun in the early part of the 20th century, but widespread, frequent use was not common until after WWII. Throughout the development of inventory techniques and their application to assess the status of the nation's forests, most of the work has been done by the USDA Forest Service through regional centers. Various sampling designs have been tried: some have proved efficient for estimation of certain parameters but not others. Some designs, though efficient in many respects, have been abandoned due to the complexity of application. Others, while possibly not demonstrating high efficiency, have been adopted because of the simplicity of application. This is a history of these applications. We start with the early compilations of western data and line-plot cruises for statewide inventories. Much discussion is presented on the development of specialized designs for regional applications that mushroomed from the 1940's through the 1970's. We conclude with descriptions of the various designs now in common use or being tested today.

One of the first notices of the awareness of a need for a national forest inventory is found in "Timber Depletion and the Answer" (Greeley 1920). This report stated that "The original forests of the United States are estimated to have covered 822 million acres and to have contained 5,200 billion board feet of timber....There are left today about 137 million acres of virgin timber, 112 million acres of culled and second-growth timber large enough for sawing, 133 million acres partially stocked with smaller growth, and 81 million acres of devastated and practically waste land....Three-fifths of the timber originally in the United States is gone." The main point of the report is a call for legislation to protect forest land from fire and to increase the area of public land. One small section of the report does suggest that "legislation is needed, with an appropriation of $3,000,000, to be available for from 2 to 4 years as the work may require, which will permit the Secretary of Agriculture to survey the forest resources of the United States, determine the present volume together with the present and possible production of each class of timber in every important forest region...". These remarks are given in more detail in a report of the same year known as "The Capper Report." The USDA Forest Service views this report as the first of a series that incorporated new data and it was considered a milestone in appraising our timber supply.

Although the Capper Report is a milestone, our main consideration in this paper is the historical development of sampling methods to collect data and to make inferences. This report includes many inferences as summarized in the Chief's report, but it includes the admission that "A comprehensive and fully adequate report...would require an exhaustive survey of the forest resources of the country...No such survey has ever been made." It was pointed out that "data...have been compiled from a great variety of sources secured for different purposes by different organizations with varying degrees of accuracy."

The second milestone report, the Copeland Report, was prepared by the Forest Service in 1930 and presented to Congress in 1933. It included such new data as had become available to supplement the data of the Capper Report, but there was still no "grand sampling design" to acquire data.

The McSweeney-McNary Forest Research Act of 1928 had earlier authorized the Forest Service to conduct a national forest survey. It called for "a determination of the present and potential productivity of forest land therein (the United States)." Because the main concern in those days was the timber situation, it was understandable that the survey was primarily a timber inventory. The survey began in 1930 (Andrews 1932, Wilcox 1938) in Oregon, McNary's home state, as described by Doig (1976). Planning had begun in 1929 when Thornton T. Munger, the first Director of the Pacific Northwest Forest Experiment Station, received $30,000 in funding (Van Hooser *et al.* 1992). The first approach in the Pacific Northwest was to use available private data with some field work for verification and supplementation. Doig described an experiment carried out in 1930-1931 in Lewis County, WA, in which a line-plot survey was run to compare it with compilations made for the area and to

---

Dean, School of Forestry and Wood Products, Michigan Technological University, Houghton, MI, USA, and Professor Emeritus, Yale School of Forestry and Environmental Studies, New Haven, CT, USA, respectively.

assess its potential for use in the South. Plots were one-quarter acre in size and spaced at 10-chain intervals on east-west strips run through forested areas. About 486 miles of survey line had been run by the end of June 1931. The field work had included 3,888 sample plots at a cost of $10,448. It was decided not to use the method in the Douglas-fir region because of the rugged terrain, but it was adopted for the East.

Some results for Oregon and Washington were published in 1932 (Cowlin). A later report was published for the Douglas-fir region (Anonymous 1934). Wieslander (1935), who was head of Forest Survey at the California Forest and Range Experiment Station from 1935 until 1950, described the first steps of Forest Survey in California. He said that mapping was in progress, and there was a plan to take 35,000 field plots, but this was not done until after 1950. Wijkstrom (1930) described a sample plot method used in a land economic survey for Minnesota. It's not clear whether this was part of the new nationwide Forest Survey.

"Cap" Eldredge was placed in charge of Forest Survey in the South, headquartered at the Southern Forest Experiment Station in New Orleans in 1930. Two reports in 1931 (Anonymous, Lentz) described the line-plot sample method (based on the Lewis County, WA, experiment) that was proposed for 25 million acres of bottomland area in the Mississippi Delta states. Two interim reports on this were made in 1932 (Anonymous, Lentz). Lentz' report stated that 5,815 plots had been taken on 4,425,000 bottomland acres; Eldredge (1935) noted that field inventory of 75 million acres in the South would be completed by April 1, 1935. A second report by Eldredge (1937) described methodology consisting of three-man crews on parallel compass lines 10 miles apart taking quarter-acre plots at 10-chain intervals. He stated that analysis had begun and that some results had been published.

In 1938, Garver reported that the forest inventory phase was well along in the South, Pacific Northwest, and the Lake States. He said the job was half done—289 million acres of forest land had already been examined. There was no information on sampling design, intensity, etc. Cunningham (1939a,b) reported that the inventory phase of Forest Survey in the Lake States had been completed in 1937, and he reported preliminary statistics on areas and volumes. Forest Service Chief F. A. Wilcox stated in his annual report (1938) that "We need in forests all the 630 million acres we now have and that are most valuable for forest growth. Yet unless it is abused and neglected, we probably do not and will not need more forest land. For 300 years our forests have been chopped, burned, and depleted. Yet with care and forethought there seems no excuse for a timber famine of national proportions." He also stated that "The Forest Survey indicates that we have more forests than we thought,...and more forest growth." It was also pointed out that the Forest Survey had begun in 1930, and about one-half of the forests of the United States had been surveyed—with about 60 percent of the resulting data compiled. This was the status that remained for several years, due to the war. Several tables of information on the status of the nation's forests were presented by R. E. Marsh, Acting Chief, and William H. Gibbons, Senior Forester, Division of Forest Economics, Forest Service, in the 1940 Yearbook of Agriculture. They noted that reports and unpublished manuscripts by many members of the Forest Service had been drawn upon. "Where authoritative data on forest conditions such as those so far furnished by the Forest Survey have been available, they have been used. Where such data were not available, the best approximations possible, which are believed to be substantially near the truth, have been made." This is considered by the Forest Service as the third milestone report.

Shortly after the war, Forest Survey began in earnest. In two reports in 1946, Chief Lyle F. Watts said that "during 1945 and 1946 the Forest Service has been making a reappraisal of the Nation's forest situation." Several tables were presented, and the general conclusion was that there was enough forest land, but not enough timber. The survey was credited to R. E. Marsh, and the data were compiled and presented by C. Edward Behre and S. Blair Hutchison. These reports make up the fourth milestone report.

The four milestone reports portrayed national results, but there is little information on how they were obtained. The purpose of this paper is to present the historical development of sampling as used in the national Forest Survey. Most survey efforts based on extensive sampling of the nation's forests began in 1930 or later. The actual sampling designs used began to appear more commonly in the literature in the 1950's. As pointed out in an excellent portrayal of the roots of forest inventory in America by Gregoire (1992), one of the first (if not the first) sampling texts was prepared specifically for forestry by Schumacher and Chapman (1942).

Becker (1950) described the Forest Survey procedures used in the Central States. This effort was a function of the Central States Forest Experiment Station in Columbus, OH, where Becker was Field Supervisor for Forest Survey. He said that the first field work began in the Pacific Northwest in 1930 and was gradually extended to other areas. As indicated earlier in this paper, he explained that most of the effort in the West was based on compilation of available data. He indicated that a line-plot system was used in other areas, including the central states where the effort began in 1946. He explained that area estimates in the central states were based on aerial photo plots and that a subsample of these plots were field-sampled to obtain volume estimates. He also indicated that a type of optimum allocation was used (at least a disproportional allocation). A higher intensity of field plots was used in sawtimber stands than in poletimber stands, and a higher intensity in poletimber than in seedling/sapling stands.

The reference to line-plot field inventory brings to mind a story related 40 years ago by Fred Hampf, who took part in the first Forest Survey of Virginia. He said that he walked across Virginia three times (east-west). He said that as he was approaching the Natural Bridge, he offset his line so that he would go directly under it. He claimed to be doing "government work" so that he wouldn't have to pay admission. Hundreds of foresters who have taken part in Forest Survey work over the past several decades most certainly have their memories of favorite plots and stories.

In the Pacific Northwest, the problems of estimating volumes in old-growth stands presented a different type of challenge than faced in the East. Floyd Johnson, a statistician at the Pacific Northwest Forest and Range Experiment Station, began working on this (Johnson 1950, Johnson and Hixon 1952). At that time—and up to current times—the approaches taken in Forest Survey differed somewhat at the different experiment stations. Some of this difference was needed. The large ownerships and high volumes in parts of the West seemed to necessitate a cooperative approach between agencies and private owners with most wanting the survey results to be useful in management planning. The smaller ownerships and generally lesser volumes by individual owners east of the Rockies enabled the stations in the East to design broad inventories, produce state reports, and—for the most part—leave management planning for individual owners as a separate problem faced by those owners. Much of this was good, but it presented problems that also have continued to this day. The autonomy of the individual stations meant that differences in techniques appeared even when there would have been advantages gained by standardization.

The approach of using aerial photo plots and ground plots in combination to estimate areas and volumes had been apparent for some time and was probably best described by Bickford (1952). He pointed out that the use of photo plots to form strata and to estimate their sizes, along with a subsample of those plots being measured as field plots, is a double sampling design. Specifically, it could be called stratified sampling with estimated stratum weights. He relied heavily on Neyman (1938), and shortly after on Cochran (1953), when the first edition of his popular textbook was published. It's interesting to note that the formula for estimating variance in Cochran's earliest edition was incorrect. It was corrected in a later edition and was extended to the case of n-phase sampling by Frayer *et al.* (1979) and Jeyaratnam *et al.* (1984). These later works were among many in the literature in the 1970's when it appeared that some combination of satellite imagery, aerial photos, and ground plots would be useful in multiphase or multistage estimators.

The use of aerial photos to set up strata, simple as it seems, sometimes was confusing and was not always done to best advantage. Of course, the more recent the photographs, the higher the correlation between what could be interpreted from them and what was found on the field plots. Some people just would refuse to believe that photos a few years old could help to provide estimates of today's areas and volumes. Inefficiencies occurred when many strata were used, and photo interpreters spent a long time classifying the photo plots. Take, for example, the case where only two strata are used: nonforest and forest. Plots that interpreters were uncertain of often resulted in long discussions, and sometimes it was a tossup where they went. Because only a small portion of plots fell in this category, it was much more efficient to place them in an "unknown" third stratum (Frayer 1978). Early work by Bickford showed the advantages of optimum allocation. However, over time, strata change, objectives may change, personnel most certainly change; and all of these factors argue for a simple, easily understood approach. Proportional allocation became more common over time.

Wheeler and Cruikshank published an article in 1956 titled "The South's Forest Resource." Wheeler and Cruikshank were, respectively, Chiefs of the Division of Forest Economics at the Southern Forest Experiment Station, New Orleans, LA, and the Southeastern Forest Experiment Station, Asheville, NC. It was a report for the combined station territories. The two stations later went somewhat their own ways, and it was only recently (culminating with the combination of the two Forest Survey units) that data and information could be easily combined for the states covered in the earlier report.

Several things happened in the early 1960's that resulted in changes in design and measurement techniques at several experiment stations. Point sampling had become very popular (Bitterlich 1948; Grosenbaugh 1952,1958; Beers and Miller 1964). The realization that remeasured plots were the most precise way to estimate growth and change was acknowledged (Hall 1959). Shiue (1960) and Shiue and John (1962) proposed systematic sampling with multiple random starts. To the purist, this had some appeal because it satisfied statistical theory and, at the same time, provided a consistent way of locating plots on maps, topo sheets, and photos. Over time, however, it had been used only at the North Central Forest Experiment Station, and they abandoned it to be more consistent with other stations. Sampling with partial replacement, the most complicated design ever used by Forest Survey, was implemented at the Northeastern Research Station (Ware 1960, Ware and Cunia 1962, Bickford *et al.* 1963). In time, sampling with partial replacement was dropped, primarily because of its complexity (Scott and Kohl 1992). Foresters in the West were adopting some of the eastern procedures, such as combining aerial photo information and ground plots (MacLean 1963).

Fixed-radius plots were abandoned in most places in favor of point samples. This was an especially interesting development that provided for precise estimates of volume by sampling trees with probability proportional to basal area. At the same time, components of change were receiving prime attention (Hall 1959, Beers 1962). A sweeping change to point sampling was accompanied by development of estimation procedures for growth components on remeasured points. Most stations were now using a cluster of 10 points roughly covering an acre. In the East, it was decided that it would be reasonable to sample approximately 20 trees on each cluster. Because it was generally accepted that 75 square feet of basal area was the minimum for a fully stocked stand, some stations started using 37.5-factor prisms (75 ft^2 divided by 20 trees times 10 points = 37.5).

All these activities in the early 1960's may have been the result of the fifth milestone report prepared by the USDA Forest Service (USDA 1958). To prepare information for this 713- page report, data were compiled in a number of ways: states that had been surveyed since January 1, 1947, were based on the survey data; for 10 states in which the survey was in progress, the data collected were supplemented with some additional data; and for other states, special surveys were conducted to gather some information. This large effort, coupled with the fact that there were now competent statisticians at the experiment stations and forestry schools, probably helped provide the impetus for the myriad studies and publications of the early 1960's.

Another USDA Forest Service milestone report was released in 1965. Titled "Timber Trends in the United States," it was based on more complete data than any previous report. It includes description of a stand-projection procedure used to standardize data to a common year for publication and to provide projections for the future. Some simulation studies using this procedure later showed that rates of change (harvest and growth components) are especially critical for such a projection procedure to have any precision (Frayer and Jones 1970).

The 1970's saw continued emphasis placed on Forest Survey. The original enabling legislation, the McSweeney-McNary Forest Research Act of 1928, was first amended by the Forest and Rangeland Renewable Resources Planning Act of 1974 and later by the National Forest Management Planning Act of 1976. The overall result was more responsibility and more funding for Forest Survey. Forest Survey by this time was known as Forest Resources Evaluation Research and later as Forest Inventory and Analysis. For the purposes of this paper, we use the term Forest Survey throughout. Satellite data were now readily available (Langley 1971). It was shown that combinations of high-altitude photography, low-altitude photography, and field samples could form the basis for effective three-phase sampling in Forest Survey (Kent *et al.* 1979, Johnston 1982). It was assumed that sampling of many resources—not just timber—was needed (Frayer 1974, 1978; McClure *et al.* 1979; Furnival 1979). Some (Scott 1979) thought that interim data were needed (survey cycles ranged from less than 10 years in some states to almost 20 years in others). There was talk about producing estimates on an annual basis (Frayer 1978), an idea that is at the forefront of two ongoing Forest Survey studies (AFIS and SAFIS) described later. Another milestone report was published titled "Outlook for Timber in the United States" (USDA Forest Service 1973). A stand projection system was again used to bring data to a common year (Larson and Goforth 1974). Peden *et al.* (1973) described how variance estimators could be used with these projections.

Forest Survey in many ways had matured. Many studies were carried out over the next 2 decades. Some were done within the Survey units, and many were done in conjunction with the Survey Techniques Project, which has been located at the Rocky Mountain Research Station since the late 1970's. Two of the studies currently being conducted and which will be described later have already been mentioned (AFIS and SAFIS).

The maturity of Forest Survey was evidenced by publications for states, parts of states, and periodic milestone reports for the nation, as required by enabling legislation. Sampling designs were now mostly in place for the various stations, although there continued to be differences among stations. The information in the following several paragraphs describes the procedure in place for each station and is based largely on an excellent in-house report of the Forest Service (USDA Forest Service 1992).

Pacific Northwest Research Station

The PNW Station covers the West Coast, including Alaska and California. Responsibility for California had originally been assigned to the station in California (now the Pacific Southwest Research Station). Two approaches are used. In Alaska, sample populations are first identified by broad vegetation classification based on satellite digital data. Within these populations, the primary sample consists of a random selection of satellite pixels transferred to aerial photographs. Items classified on the primary photo samples include land class, ownership, forest type, and timber volume class. Secondary samples for ground examination are selected from the primary samples. All strata are sampled, but the sampling intensity on non-forest strata is less than in forested strata. In other Pacific Coast states, the primary sample is defined by a systematic grid of permanent, mapped points. At each grid point, aerial photos are used to classify the land into strata similar to those used for Alaska. Secondary samples for ground examination are selected systematically from the primary sample locations. Secondary sample intensity can be varied to meet special objectives.

Intermountain Research Station

This Station has had responsibility for the Rocky Mountain West and the Southwest. The general approach is a stratified double sampling design. The primary sample is defined by points on a systematic 1,000-m grid. Each grid point is located on an aerial photograph for interpretation. Items identified for stratification include ownership, land class, and forest type group. The interpreted items are used to define sampling strata. The secondary ground sample is a subset of the primary sample at 5,000-m intervals. A supplemental 5,000-m field grid is available for sampling intensification as required by cooperators, and additional samples can be selected from the 1,000-m primary grid.

North Central Research Station

The North Central Station has responsibility for the midwestern states and lake states (the Central States Station was phased out in the 1960's). Using a systematic grid of 121 plots per township (36 square miles or 9,324 ha) on aerial photographs, each photo plot is classified stereoscopically based on land use, forest type, size, and density. Areas are allocated to ground locations, which are a systematic subsample of the photo plots using random allocation. The total number of ground plots sampled in an inventory is a function of the expected variability of the resource, the expected accuracy of the aerial photo interpretation, and the desired sampling errors.

Southern Research Station

Until recently, the Southern Station has had responsibility for states in the mid-South. This station was recently combined with the Southeastern Station, and the work handled by both will now be headquartered in Asheville, NC.

Estimates of timberland area are based on forest-nonforest interpretation of plots on aerial photographs. These plots represent approximately 230 acres (93 ha). The land-use interpretations are checked in the field at sample locations representing approximately 3,840 acres (1,554 ha). After these checks are used to adjust the photo interpretations, an estimate of the proportion of forest to non-forest area is then made for each county. The proportion of forest area is combined with U.S. Census land area data to derive county-level forest area statistics.

Descriptive forest resource statistics are derived from measurements at permanent sample plots located at the intersections of a 3- by 3-mile (4.8- x 4.8-km) grid; each plot represents, on average, 5,760 acres (2,331 ha). The sample plots are remeasured at each survey to allow assessment of change (i.e., growth, removals, and mortality estimates) and of current resource status.

At each forested sample plot on the 3-mile (4.8-km) grid, trees are measured on a cluster of 10 sample points. Trees at least 5.0-in. (12.7-cm) dbh are selected using a 37.5-factor prism; each sample tree thus represents 3.75 ft^2 (0.35 m^2) of basal area. Trees smaller than 5.0-in. (12.7-cm) dbh are sampled on a 1 /275-acre (0.0015-ha) circular plot at the first three points of the 10-point cluster. Using several tree measurements, volumes are computed using Smalian's formula.

Southeastern Research Station

In the first phase (of a two-phase design), a large number of 16-point cluster samples are interpreted from aerial photographs for forest, non-forest, and non-census water land use. In phase 2, a smaller set of 16-point cluster samples are centered over each permanent ground sample and classified in the same manner as described above and then checked on the ground. The 16-point clusters checked on the ground are used to adjust the area estimates from the photo sample. A linear regression is fitted to develop a relationship between the photo and ground classification of the subsample. The entire photo estimate in phase 1 is adjusted for change in land use since the date of photography and for misclassifications.

The inventory volume design consists of all the permanent sample points that fall on timberland. These are used for volume per acre estimates, number of trees, and stand attributes. Each permanent forest inventory sample that is relocated and remeasured is used to estimate growth, removals, and mortality.

Northeastern Research Station

Responsibility for northeastern states, including west to and including Ohio and south including Maryland. A primary sample is obtained from a grid of photo points overlaid on aerial photographs of the inventory area. Interpretation of each photo point is for land use and timber volume class stratification. A secondary sample is taken for on-the-ground examination; samples include all ground plots measured at the last occasion and new ground plots that are added to make the ground sample proportional to the primary sample. Data from all plots, new and remeasured, are combined to calculate a combined estimate of current volume.

If you were to try to characterize the descriptions, you could say that most states are inventoried with a double sampling design, using photo plots for stratification and ground plots for volume measurements. You can readily see many differences. This is one factor that led to the formation of a Blue Ribbon Panel on Forest Inventory and Analysis. Its report (Anonymous 1992) had many recommendations, including to "increase consistency and compatibility among FIA (formerly Forest Survey) units." A second Blue Ribbon Panel was assembled in 1997. Its report is in the review process. It is expected that two of the things to be stressed are support for an annual inventory system and strong support for standardizing plot configuration.

The Forest Service has already moved to standardize plots to a cluster of four fixed-radius plots. This may end an era lasting close to 40 years in which the most popular plot was a cluster of 10-point samples.

AFIS and SAFIS Studies

We'll close with a discussion of two important studies now underway. The first of these, being tried in northern Minnesota, is the Annual Inventory System (AFIS). Briefly, it is an attempt to use remote sensing (satellite data in this case) to stratify plots into classes with different probabilities of disturbance. Those with higher probabilities of disturbance would have a higher probability of being sampled in a given year, while other plots would be updated using models.

The Southern Annual Inventory System (SAFIS), being tested in Georgia, is similar, but probabilities of field plot selection will be equal (proportional allocation). Values for unmeasured plots may be inputted or estimated from models. Thus, the results at first may not be as precise (for a given effort) as the AFIS approach if the stratification by satellite imagery is successful, but the SAFIS group is avoiding the long-term complexities of using unequal probabilities with stratum boundaries changing over time. Plus, the more rapid changes (in land uses as well as volumes) in the South probably reduce the gains possible from optimum allocation. For example, one possible approach that was voiced at the Southeastern Station in the 1960's was to fly over forested plots in a light plane and then remeasure those that appeared disturbed. This could have been a reasonable way of estimating volume change. However, for determination of forest area, the changes from non-forest to forest area might be of more importance than the disturbed forested plots.

SUMMARY

We have described the development of inventory techniques to assess the nation's forest resources. We have mentioned some of the national reports and some of the personnel who were involved in the early days of Forest Survey. We have concentrated more on the sampling designs used than on the development of measurement procedures and their changes over time. Current emphasis in Forest Survey is on development of sampling designs and models that will provide annual information.

LITERATURE CITED

Andrews, H.J. 1932. Forest survey in the Douglas fir region. Journal of Forestry. 30: 264-275.

Anonymous. 1931. Second phase of forest survey gets under way. Journal of Forestry. 29: 616-617.

Anonymous. 1932. Preliminary forest survey completed in south. Journal of Forestry. 30: 624-625.

Anonymous. 1934. Forest survey statistics available. Journal of Forestry. 32: 879.

Anonymous. 1992. Report of the blue ribbon panel on forest inventory and analysis. 14 p.

Becker, M.E. 1950. Forest survey procedures for area and volume determination. Journal of Forestry. 48: 465-469

Beers, T.W. (1962) Components of forest growth. Journal of Forestry. 60: 245-248.

Beers, T.W.; Miller, C.I. (1964) Point sampling: research results, theory and applications. Res. Bull. 786. Purdue University.

Bickford, C.A. (1952) The sampling design used in the forest survey of the northeast. Journal of Forestry. 50: 290-293.

Bickford, C.A.; Mayer, C.E.; Ware, K.D. (1963) An efficient sampling design for forest inventory: the Northeastern forest resurvey. Journal of Forestry. 61: 826-833.

Bitterlich, W. 1948. Die winkelzahlprobe. Allgemeine Forst-und Holzwirtschaftliche Zeitang 59: 4-5.

Cochran, W.G. 1953. Sampling techniques. New York, NY: John Wiley & Sons. 320 p.

Cowlin, R.W. 1932. Areas of types in Oregon and Washington counties. Journal of Forestry. 30: 504-505.

Cunningham, R.N. 1939a. Preliminary forest survey figures from the lake states. Journal of Forestry. 37: 66-69.

Cunningham, R.N. 1939b. Lake states forest survey. Journal of Forestry. 37: 698-700.

Doig, I. 1976. When the Douglas-firs were counted: the beginning of the forest survey. Journal of Forest History. 20: 21-27.

Eldredge, I.F. 1935. The south's forest survey. Journal of Forestry. 33: 406-411.

Eldredge, I.F. 1937. Sawtimber and cordwood volumes in central and southwestern Mississippi. Journal of Forestry. 35: 504-505.

Frayer, W.E. 1974. The increasing complexity of large forest inventories. Journal of Forestry. 72: 578-579.

Frayer, W.E. 1978. Objectives of multi-resource inventories in relation to design considerations. In: Integrated inventories of renewable natural resources. Gen. Tech. Rep. RM-55. Fort Collins, CO: Rocky Mountain Forest and Range Experiment Station: 267-269.

Frayer, W.E. 1978. Stratification in double sampling — the easy way out may sometimes be the best way. Resour. Inven. Notes 10: 1-3. Denver. CO: U.S. Department of Interior, Bureau of Land Management.

Frayer, W.E. 1978. Potential uses of sampling with partial replacement in national inventories. In: Proceedings of IUFRO conference on forest inventories. Bucaresti, Rumania.

Frayer, W.E.; Jones, D.B. 1970. Effect of estimated inputs on the output of a stand-projection system—a Monte Carlo approach. Department of Forest and Wood Sciences, Colorado State University. 8 p. (Also, Abstracts, Society of American Foresters Annual Meeting, 1968).

Frayer, W.E.; Graybill, F.A.; Jeyaratnam, S.; Bowden, D.C.; Kent, B.M.; Johnston, D.C. 1979. Multilevel sampling designs for resource inventories. Colorado State University. 113 p.

Furnival, G.M. (1979) Forest sampling - past performance and future expectations. In: Forest resource inventories proceedings. Colorado State University: 320-326.

Garver, R.D. 1938. The nationwide forest survey. Journal of Forestry. 36: 889-892.

Greeley, W.B. 1920. Timber depletion and the answer. Dept. Circ. 112. Washington, DC: U.S. Department of Agriculture.

Gregoire, T.G. 1992. Roots of forest inventory in North America. Paper presented at the Inventory Working Group session of the 1992 Society of American Foresters National Convention.

Grosenbaugh, L.R. 1952. Plotless timber estimates. New-fast-easy. Journal of Forestry. 50: 32-37.

Grosenbaugh, L.R. (1958) Point sampling and line sampling. Probability theory, geometric implications, synthesis. Occas. Pap. 160. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 34 p.

Hall, O.F. 1959. The contribution of remeasured sample plots to the precision of growth estimates. 1959. Journal of Forestry. 57: 807-810.

Jeyaratnam, S.; Bowden, D.C.; Graybill, F.A.; Frayer, W.E. 1984. Estimation in multiphase designs for stratification. Forest Science. 30: 484-491.

Johnson, F. (1950) Estimating forest areas and volumes of large tracts. Journal of Forestry. 48: 340-342.

Johnson, F.A.; Hixon, H.J. (1952) The most efficient size and shape of plot to use for cruising in old growth Douglas-fir timber. Journal of Forestry. 50: 17-20.

Johnston, D.C. (1982) Theory and application of selected multilevel sampling designs. Colorado State University. 194 p. Ph.d. dissertation.

Kent, B.; Johnston, D.; Frayer, W.E. (1979) Application of three-phase sampling for stratification to multi-resource inventories. In: Forest resource inventories proceedings. Colorado State University: 993-1000

Langley, P.G. (1971) Multistage sampling of earth resources with aerial and space photography. In: Monitoring earth resources from aircraft and spacecraft. NASA SP-275, Washington, DC: 129-141.

Larson, R.W.; Goforth, M.H. (1974) TRAS: a timber volume projection model. Tech. Bull. 1508. Washington, DC: U.S. Department of Agriculture, Forest Service. 15 p.

Lentz, G.H. 1931. The forest survey in the bottom-land hardwoods of the Mississippi delta. Journal of Forestry 29: 1046-1059.

Lentz, G.H. 1932. Forest Survey of the Mississippi delta region. Journal of Forestry. 30: 1015.

MacLean, C.D. 1963. Improving forest inventory area statistics through supplementary photo interpretation. Journal of Forestry. 61: 512-516

Marsh, R.E.; Gibbons, W.H. 1940. In: 1940 Yearbook of Agriculture: 458-488.

McClure, J.P.; Cost, N.D.; Knight, H.A. (1979) Multiresource inventories-a new concept for forest survey. Res. Pap. SE-191. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 68 p.

Neyman, J. 1938. Contribution to theory of sampling human populations. Journal of American Statistics Association. 33: 101-116.

Peden, L.M.; Williams, J.S.; Frayer, W.E. 1973. A Markov model for stand projection. Forest Science. 19: 303-314.

Schumacher, F.X.; Chapman, R.A. 1942. Sampling methods in forestry and range management. Bull. 7. Duke University, School of Forestry. 213 p.

Scott, C.T. (1979) Midcycle updating: some practical suggestions. In: Forest resource inventories proceedings. Colorado State University: 362-370.

Scott, C.T.; Kohl, M. 1992. Experiences with designing the forest survey of the northeastern United States. In: Proceedings of the 100th I. U. F. R. O. World Congress, Berlin.

Shiue, C.J. (1960) Systematic sampling with multiple random starts. Forest Science. 6: 42-50.

Shiue, Cherng-Jiann; John, H.H. 1962. A proposed sampling design for extensive forest inventory: double systematic sampling for regression with multiple random starts. Journal of Forestry. 60: 607-610.

USDA Forest Service. 1920. Timber depletion, lumber prices, lumber exports, and concentration of timber ownership. Report on Senate Resolution 311, 66th Congress, 2nd session. 71 p. [The Capper Report]

USDA Forest Service. 1933. A national plan for American forestry. Senate Document 12, 73rd Congress, 1st session. 2 volumes, 1,677p. [The Copeland Report]

USDA Forest Service 1958. Timber resources for America's future. For. Resour. Rep. 14. Washington, DC: U.S. Department of Agriculture. 713 p.

USDA Forest Service 1965. Timber trends in the United States. For. Resour. Rep. 17. Washington, DC: U.S. Department of Agriculture. 235 p.

USDA Forest Service 1973. Outlook for timber in the United States. For. Resour. Rep. 20. Washington, DC: U.S. Department of Agriculture. 367 p.

USDA Forest Service 1992. Forest resource inventories: an overview. Washington, DC: U.S. Department of Agriculture, Forest Service. 39 p.

Van Hooser, D.D.; Cost, N.D.; Lund, H.G. 1992. The history of the forest survey program in the United States. In: Proceedings of the 100th I. U. F. R. O. World Congress, Berlin.

Ware, K.D. (1960) Optimum regression sampling design for sampling of forest populations on successive occasions. Yale University. Ph.D. dissertation.

Ware, K.D.; Cunia, T. (1962) Continuous forest inventory with partial replacement of samples. Forest Science Monograph. 3.

Watts, L.F. 1946. Timber shortage or timber abundance? Report of the Chief of the Forest Service. Washington, DC: U.S. Department of Agriculture, Forest Service.

Watts, L.F. 1946. Gaging the timber resource of the United States. Washington, DC: U.S. Department of Agriculture, Forest Service. 66 p.

Wheeler, P.R.; Cruikshank, J.W. 1956. The south's forest resource. Journal of Forestry. 54: 629-632.

Wieslander, A.G. 1935. First steps of the forest survey in California. Journal of Forestry. 33: 877-884.

Wijkstrom, S. 1930. Sample plot method of the Minnesota land economic survey for determining growth and yield. Journal of Forestry. 28: 734-738.

Wilcox, F. A. 1938. Report of the Chief of the Forest Service. Washington, DC: U.S. Department of Agriculture, Forest Service.

Rebuilding Our Legacy Inventories: Identifying the Good and Fixing the Bad

Dave Gilbert, Keith Tudor, Sam Otukol, and Karen Jahraus

Abstract.—Several challenges faced the Province of British Columbia in the early 1990's as we undertook a major redesign of our inventory systems: a provincial legislated demand requiring the chief forester to develop and maintain an inventory of the land and forests in British Columbia; existing inventories of the 94.5 million ha of the province; the need to meet new information requirements to address criteria of sustainable forest management and their associated indicators; the need to link previously almost disparate systems in growth and yield and inventory through common sampling and monitoring protocols; and little possibility of significant new resources.

The three papers presented in this session provide a management perspective, the technical details of the design and its current implementation, and the significant issues in the development and delivery of the training program to deliver this inventory.

This paper presents the historical background of the current inventory design, its implementation over the last 30 years with its strengths and weaknesses, the audited state of the existing inventory, the drivers of the new design, and the associated constraints with any new design.

As always when implementing change, the change in corporate culture is the most significant issue. The notion of sampling to provide population statistics that in turn adjust initial estimates has been foreign to most practitioners in the province. A review of the reliability of the existing inventories as gleaned through audit procedures, along with an assessment of our ability to photo-interpret inventory strata, is also provided.

> "***Sadly, the state of renewable forest resources inventories in this province is inconsistent at best, and woefully inadequate at worst***" (Forest Resources Commission, April 1991).

What a rude awaking, almost 13 months to the date of being appointed as the Director of the Resources Inventory Program of the Ministry of Forests when an impartial commission, the Forest Resources Commission, reported April 1991, to the then Minister of Forests.

Several issues, one of which was the adequacy of the inventories of the natural resources of the province, were reviewed by the commission. On the subject of natural resource inventories, the commission recommended that:

> "***The government immediately examine and implement ways by which the full range of forest related inventories can be made standard and able to be used on compatible systems while, at the same time, retaining the values for which they were originally intended***" (Forest Resources Commission, April 1991).

As the new guy on the block, I could only hope that the Commission's report was a comment on the legacy that I had inherited and not the current Director!

The reality was accurately portrayed by the commission. The province possessed an inventory of its timber resources that was old and aging fast. The timber inventory had its origin in the 1960's when the prime motivation was timber volume to feed an expanding forest industry, and as a result, information on other forest values was non-existent. Further inventories of other values, fisheries, wildlife, and rare and endangered

---

Dave Gilbert, Director, Resources Inventory Branch, BC Forest Service; Keith Tudor, Coordinator, Vegetation Inventory, Resources Inventory Branch, BC Forest Service; Statistician, Sam Otukol, Statistical Decision Support, Resources Inventory Branch, BC Forest Service, P.O. Box 9516, Station Prov. Govt., Victoria, BC, V8W 9C2, respectively; and Karen Jahraus, Jahraus and Associates Consulting Inc., 707 Moss St., Victoria, BC, V8V 4N9, Canada.

species were almost non-existent due to chronic underfunding.

This paper and the two following, by Dr. Kim Iles and Mr. Norm Shaw, will discuss the response of the province and industry to the challenge presented by the Forest Resources Commission.

This paper provides the framework by:

- outlining the size of the province, the state of ownership, and the scale and importance of the industry;
- outlining progress that has been made to develop compatible inventory standards and procedures for all resource inventories;
- describing the state of the existing inventories, their origin, and the ongoing management process for those inventories;
- presenting the results of the audit of the provincial timber inventories; and,
- describing the emerging issues that we are facing.

Dr. Iles will describe:

1. Development of the vegetation resources inventory.
2. Dynamics of the committee structure.
3. Education: the lessons learned.

Mr. Shaw will describe:

1. Development of the training program.
2. Delivery of training including certification of field staff.
3. Delivery of the program.

BC: Just Where Is That Foreign Country?

British Columbia, one of the 12 provinces and territories of Canada, spans 12 degrees of latitude from 48 degrees to 60 degrees and 25 degrees of longitude from 114 degrees to 139 degrees. The province covers 95 million ha. Placed in comparison, the province covers almost as much land area as the Pacific Northwest States of Washington, Oregon, Montana, and Idaho in the U.S. For our visitors from Europe, British Columbia is larger than the countries of France, Germany, and Belgium combined.

The Province of British Columbia manages as much forest land as the United States Forest Service.

The forest sector is the mainstay of our provincial economy. British Columbia derives 7 percent of its provincial gross economy from the forest industry. We are an export economy, exporting to Europe, Japan and Southeast Asia, and to our largest market, the United States.

Unlike the United States, 95 percent of British Columbia is owned by the Crown, and land use, in particular the forest sector, is regulated under law. The chief forester of the province, my boss, determines the Allowable Annual Cut (AAC) for each of the 71 management units in the province. The current AAC is set at 70.855 million m^3 per year.

Responding To The Recommendation Of The Forest Resources Commission

In response to the Forest Resources Commission recommendations, a multisectoral, multiagency Resources Inventory Committee (RIC) was established in 1992, to address the issues of standards and coordination of forest resource inventory information.

RIC is responsible for establishing standards for natural and cultural resources inventories, including collection, storage, analysis, interpretation, and reporting of inventory data. The range of standards required to deliver an inventory program goes beyond just field inventory, and includes discipline standards, field inventory standards, digital data standards, use or interpretation standards, and product standards.

From its inception, the committee attempted to answer questions in two critical areas:

1. **Land Management**. Vital information for effective land management, levels of detail, and for what purposes?
2. **Efficient information**. How can this information be most efficiently acquired in a manner that minimizes duplication, promotes cooperative data collection, and encourages broad application and long-term relevance?

The committee's objectives focus on standards for the collection and application of forest resources data. The approach was:

1. **Collection**. Determine who has been collecting what resource inventory information, to what standards, and using what procedures.
2. **Requirements**. Identify the information products that will be needed most by resource managers and the associated inventory needs.
3. **Standards and Procedures**. Develop, where appropriate, common standards and procedures in both the government and private data collection programs.
4. **Delivery**. Develop appropriate inventory-related training and extension programs and delivery mechanisms.

The approach developed by RIC to facilitate the development of common standards and procedures across a variety of private, provincial and federal jurisdiction was to establish eight task forces co-chaired by experts drawn from the appropriate agencies: Aquatic Ecosystems, Atmosphere & Air Quality, Coastal Ecosystems, Culture, Earth Sciences, Land Use, Terrestrial Ecosystems, and Infrastructure. Seven years after the establishment of this process, we can look back on the development of 97 standards and procedures. Appendix 1 provides a listing of the standards developed to date and the 17 standards still under development.

As the standards and procedures were developed, the realization dawned on the committee that a series of training programs was needed to effectively implement the program. The purpose of the RIC Training Program is to provide people involved in the collection of this information with the required skills and knowledge to properly conduct resources inventories.

The RIC Training Program is targeted at a broad range of people. Levels 1 to 3 focus on people who are new to the resources inventory field; this portion of the training program provides them with the required skills and knowledge to work as effective members of a field crew. Level 4 focuses on existing technicians and professionals. Training at this level deals with the specifics of each RIC Standard. Generally speaking, individuals taking this level of training will be the ones who will lead the various field crews in their inventory activities.

The following figure illustrates each of the levels in the training program and how they relate, and it provides a few examples of course content (fig. 1). Appendix 2 provides a complete listing of training courses developed to date.

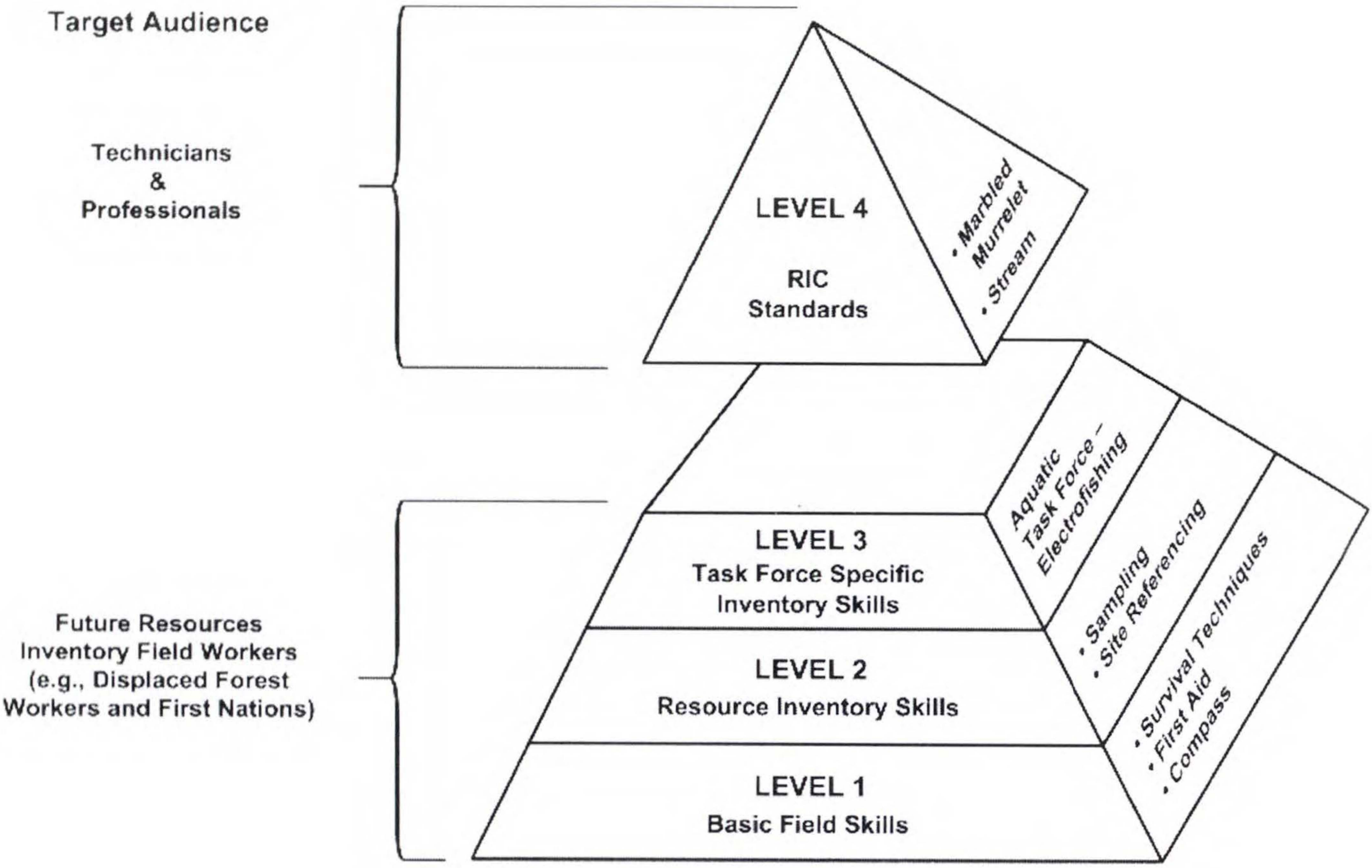

Target Audience
Technicians & Professionals
Future Resources Inventory Field Workers (e.g., Displaced Forest Workers and First Nations)
LEVEL 4
RIC Standards
• Marbled Murrelet
• Stream
LEVEL 3
Task Force Specific Inventory Skills
Aquatic Task Force – Electrofishing
LEVEL 2
Resource Inventory Skills
• Sampling
• Site Referencing
LEVEL 1
Basic Field Skills
• Survival Techniques
• First Aid
• Compass

Figure 1.—*Resource Inventory Committee (RIC) training program.*

RIC continues to function. As the development of inventory standards and procedures draws to completion, the challenge of change management becomes more critical. Given the dependency that has been created with common inventory standards, the rigor of a change management is being visited on all data custodians. This requires sufficient notice of proposed changes and the adherence to a standard that prohibits changes in standards during field season.

SCOPE OF BC TIMBER INVENTORIES

The foundation of our current timber inventory was laid during the "Unit Surveys" of 1960-1977 (Thrower 1992). Unit surveys were conducted on discrete areas of 500,000 to 5 million ha. Using 1:15480 black and white air photography, timber polygons were delineated, and attributes of these timber types were interpreted from the photos. The inventory was a basic timber inventory characterizing the land base as productive or non-productive for timbered forests, and within the timbered forests as commercial or non-commercial. For volume estimation, similar timber types were grouped into strata, and a series of randomly located temporary ground samples was installed to establish average volume lines for each stratum. The design sampling error was +/- 15 percent 19 times out of 20. The inventory concluded in 1976 as did the money for further field work and sampling.

From 1978 to 1992, the existing timber inventory was loaded into a Computer Assisted Drafting environment, IGDS, developed by Intergraph along with special purpose software written by ministry staff. As the project progressed, so did the ambitions.

The eventual design was to create a complete coverage of the province, to update this coverage for change, and to project the inventory for growth. To accomplish this latter task, the temporary volume samples, along with selected samples from our Permanent Sample Data Base, were used to develop yield functions. As such, the yield functions perform reasonably well in a stable environment, but for those forest types characterized by rapid stand structure changes, this approach obviously is less than desirable.

In 1988, a modest reinventory program began. Inventories were re-estimated using air photos. Little field work was conducted, and no new ground samples were installed.

We are on a biannual cycle of update for changes and re-projection of the inventories on a periodic or annual bases depending on business needs.

Aside from the obvious problems with this approach, we lost statistical rigor. It was not possible to estimate the accuracy of our existing inventories. With a contracting timber supply, in some management units, the accuracy of the standing inventory is critical to the robustness of the long-run harvest levels. In response to our inability to determine the accuracy of our inventories, we developed a program to audit the state of each inventory.

BC INVENTORY AUDITS - IDENTIFYING THE GOOD, THE BAD, AND THE UGLY

Pilots of a process to audit the state of an inventory began in 1992, under the direction of Dr. A.Y. Omule[1], Ministry of Forests, and Dr. Kim Iles, then of MacMillian Bloedel, Ltd.

The process was to select 50 forested samples in a systematic fashion from a sorted polygon list of the population of interest, i.e., all stands greater than 60 years of age in a management unit. A random start in each polygon was established in the office before field work began. A series of four full measure variable-radius plots and five count plots was established in each of the selected polygons. Volumes compiled from the plots in each polygon were compared to the estimated volume from the provincial data set for that polygon. Descriptive statistics and a student 't' test were compiled for each of the audits.

For each management unit, it was then possible to define the accuracy associated with the attributes and yield models used in the inventory, to identify possible strata of interest that exhibited substantial trends, and in some cases to identify specific remedies to deal with the problem strata. The key to being able to develop such a picture was reasonable consistency during the initial interpretation of the air photographs.

So how are we doing?

Table 1 provides a summary for the 40 audits that we have conducted and compiled to date. These audits cover 65.8 million ha of the province or about 2/3 of the land area and 56 percent of the 71 management units.

The provincial inventory overestimates the total forested timber volume by 5.15 percent with confidence limits from 2.70 to 7.60 percent. Of the 40 management units audited to date, only 8 (20 percent) exhibit differences that are significant from the inventory estimate. In 16 cases, the difference between the audit volume and the estimated volume derived from the inventory is less than 5 percent.

---

[1] *Dr. Omule left the Forest Service to join J. S. Thrower and Associates as the Senior Biometrician.*

Table 1. *Timber Supply Area (TSA) and Tree Farm License (TFL) Mature Volumes and Species Composition Agreement Summary*

1		2	3	4	5	7	8	11	12	19
Region		Timber Supply Area	Total TSA area (ha)	*Total productive forest (ha)	Audit volume	Label volume	Percent difference	Label over or under estimated	Means ratio	Samp siz
Cariboo		100 Mile House (94)	1,220,579	776,847	220	247	12.3	over est	0.89	50
		Williams Lake (95)	4,861,715	2,667,966	168	190	13.1	over est	0.88	50
Kamloops		Kamloops Dist (94)	1,241,731	792,991	183	179	-2.2	under est	1.02	50
		Clearwater Dist. (95)	852,080	450,578	287	300	4.5	over est	0.96	47
	=>	Lillooet (94)	1,123,819	540,266	218	178	-18.3	under est	1.22	50
		Merritt (96)	1,115,915	725,828	246	229	-6.9	under est	1.07	50
		Okanagan (96)	2,173,877	1,244,734	299	293	-2.0	under est	1.02	50
Nelson		Invermere (93)	1,018,357	416,884	238	231	-2.9	under est	1.03	78
		Golden (94)	920,167	212,141	340	308	-9.4	under est	1.10	50
		Kootenay Lake (94)	1,144,803	472,314	290	285	-1.7	under est	1.02	40
		Revelstoke (94)	503,984	168,608	353	363	2.8	over est	0.97	50
		Arrow (95)	753,948	353,053	263	265	0.8	over est	0.99	50
		Cranbrook (96)	1,391,619	560,872	189	200	5.8	over est	0.95	50
		Boundary (97)	580,109	342,135	179	163	-8.9	under est	1.10	50
Pr. George		Mackenzie (93)	6,130,617	2,474,317	187	207	10.7	over est	0.90	47
	=>	Dawson Creek (94)	2,277,753	1,233,978	191	155	-18.8	under est	1.23	50
	=>	Fort St.John (94)	4,553,553	1,548,285	162	194	19.8	over est	0.84	49
		Prince George (96)	7,512,981	4,451,602	234	258	10.3	over est	0.91	130
Pr. Rupert		Bulkley (94)	736,154	431,125	269	277	3.0	over est	0.97	50
		Cranberry (95)	76,751	44,436	403	378	-6.2	under est	1.07	40
		Cassiar (96)	13,413,228	3,073,088	96	101	5.2	over est	0.95	70
		Kalum (96)**	1,559,733	509,226	509	496	-2.6	under est	1.03	50
		Upper Nass (94/96)**	655,000	218,240	403	404	0.2	over est	1.00	49
		Lakes (97)	1,123,264	733,666	251	254	1.2	over est	0.99	50
		Morice (97)	1,498,698	864,629	240	237	-1.3	under est	1.01	50
Vancouver		Mid Coast (94)	2,214,984	744,819	494	526	6.5	over est	0.94	49
	=>	Fraser I (94)****	1,165,178	372,700	425	510	20.0	over est	0.83	46
	=>	Kingcome (95)	1,126,125	460,333	480	540	12.5	over est	0.89	50
		Soo (97)	719,503	233,546	460	516	12.2	over est	0.89	47
Cariboo		TFL 5 (94)	34,320	11,815	346	362	4.6	over est	0.96	50
		TFL 52 (95)	265,190	172,574	312	326	4.5	over est	0.96	50
Kamloops		TFL 33 (95)	8,354	4,448	318	314	-1.3	under est	1.01	40
		TFL 35 (94)	39,199	17,383	287	284	-1.0	under est	1.01	50
		TFL 18 (95)	74,571	30,528	283	311	9.9	over est	0.91	49
Nelson	=>	TFL 14 (93)	139,443	28,919	299	237	-20.7	under est	1.26	49
		TFL 23 (94)	554,981	173,005	339	362	6.8	over est	0.94	50
		TFL 3 (95)	79,250	22,611	255	292	14.5	over est	0.87	40
Pr. George	=>	TFL 30 (94)	180,766	84,757	249	298	19.7	over est	0.84	47
Pr. Rupert	=>	TFL 1 (95)	609,204	208,945	373	464	24.4	over est	0.80	50
Vancouver		TFL 37 (94)	189,851	77,861	722	788	9.1	over est	0.92	41
Total			65,841,354	27,952,053	301.5	313.1				

count 40

	Diff% ==>	5.15
	t*SEE% =>	2.45
Conf Int>	Lower ==>	2.70
	upper ==>	7.60

Note:

Percent Difference: The percent difference is calculated by (label volume - ground volume)/ground volume

* Total Productive Forest Area (does not include immature and NSR). Total Productive forest area is derived from area by leading species for all sites in age class range>4 (mature, greater than 60 yrs)

** Since productive area for Upper Nass was not available, the total productive area for Upper Nass was derived by using the ratio of the entire Kalum TSA.

**** Fraser does not include the additional 100 net operable

☐ => **Statistically Significant (95 percent level of probability)**

t= 2.02

A NOTE ON THE CONFIDENCE INTERVALS OF THE DIFFERENCE FOR THE COMPLETED TSAs

1. The area weighted difference is 5.15 percent, for the completed TSAs and TFLs, i.e., the mean volume/ha in the inventory may be larger than the actual mean vol/ha by 5.15 percent.
2. The confidence interval around this difference is (=/-) 2,45 percent, i.e., the over estimation could be as low as 2.71 percent, or as high as 7.60 percent, 19 times out of 20.
3. The confidence interval was computed by multiplying the SEE percent (1.21) by the t-value at the 95 percent level of confidence (2.02).
4. Use the above figures with caution. The numbers for total productive forest area has not been confirmed and is still considered draft. The

So overall, the total forested inventory is being overestimated by 5 percent. This result is not surprising given that most stands in the existing inventory are from the original forest. We have been harvesting that forests in general, from the best stands first. One would expect an audit of the remaining inventory to reflect a lower means than when the inventories were first developed. However, not everything is rosy; when we look in detail at specific inventories and strata within an inventory, we observe trends that are disturbing.

Our inventory is driven by the inventory label, the key elements of which are the leading species in the correct order and then the correct magnitude. We characterize the leading species into growth type groups (GTG). With a statistically unbiased data set, it is now possible to address questions that before, for the want of reliable data, were unanswerable. Reviewing GTG for each management unit, we created a list ordered from the best comparison to the worst. In one management unit, we identified the leading species correctly 88 percent of the time. In the worst unit, we identified the leading species correctly only 33 percent of the time. The median was 51 percent (slightly better than a coin toss). Further analysis suggests that our ability to determine leading species is related, not surprisingly, to the species themselves.

The prime driver of the volume, and thereby the accuracy of the inventory, is the height of the stand. In general, when we find an inventory that is significantly different from the audit, the most common error is a systematic bias in the estimate of the stand height.

In concluding this section, the development of an ability to audit an existing inventory has provided much needed insight to our commonly held conventional wisdom of our ability to photo-interpret. As coaches of elite athletes are fond of saying, *"You cannot expect improvement by doing the same thing that you have always done in the past."*

EMERGING ISSUES

Since the RIO conference, the world agenda has been greening.

First came the Criteria of Sustainable Forest Management and their associated Indicators, as codified in the Montreal Accord or the Helsinki Accord or the ITTO version. Following close behind is the international marketplace drive to certification of sustainable forest management for a landowner or industrial enterprise operating on a mix of crown and/or private lands.

In the last 8 months, we have seen the drafting of the Kyoto Accord to reduce greenhouse gas emissions by the developed nations.

Taken individually or collectively, all of these initiatives are placing incredible burdens on resource management agencies to develop, manage, and provide the relevant information that can satisfy all of these emerging issues.

Make no mistake, a company, a province (state), or a nation that fails to address these issues with the attention that they deserve will reap a whirlwind of economics effects that will not be easily overcome. At the heart of the new paradigm, the green agenda is driving market forces. Fail to present the appropriate green report card and you will no longer be allowed to play in the market game.

CONCLUDING REMARKS

At this point, it is appropriate to step aside and allow Dr. Kim Iles and Mr. Norm Shaw to describe our response to the stated needs and emerging issues that we have faced over the last 7 years.

But before I leave, I offer these lessons from our experience:

1. **Standards and Procedures**. It is possible, with considerable patience, to draw together disparate interests in resource inventories to develop common standards and procedures to the benefit of all.
2. **Planning**. Before you throw out that existing inventory to replace it with something better, invest a little upfront money to determine just what needs fixing and what can be left alone.
3. **Trust**. Do not accept the conventional wisdom in any field without asking them to provide objective evidence. Often, we have not been troubled by the facts in ascertaining our abilities.
4. **Sampling**. Most of our clients, and some of our colleagues, do not understand sampling and do not trust it. Expect to spend considerable time educating the educated.

LITERATURE CITED

Forest Resources Commission. The future of our forests, April 1991. ISBN 0-7726-1330-3.

Thrower and Associates. (1992) An historic summary of forest inventory sampling designs in British Columbia. Report to the BC Ministry of Forests, Inventory Branch, Timber Inventory Task Force. Prepared by J.S. Thrower. Victoria, BC: BC Forest Service.

Appendix 1 RIC—Standards

Name of Inventory Standard	Name of Inventory Standard
Aquatic Ecosystems	**Coastal Ecosystems**
Field Key to Freshwater Fishes of BC	Assessing Shellfish Culture Capability in Coastal BC
A Guide to Photodocumentation for Aquatic Inventory	BC Biological Shore-Zone Mapping System
Aerial Photopography & Videography Standards: Applications for Stream Inventory & Assessment	BC Physical Shore-Zone Mapping System
Bathymetric Standards for Lake Inventory -- Fish & Fish Habitat	BC Marine Ecological Classification: Marine Ecosections & Ecounits
Fish Collection Methods & Standards	Review of Aerial Video Survey Techniques & Recommendations of Survey Standards
User's Guide to the BC Watershed/Waterbody Identifier System	
Key to Cladocerans (Crustacea) of BC	**Culture (includes Recreation & Tourism)**
An Identification Guide to the Nymphal Mayflies of BC	
Key to the Species of Freshwater Calanoid Copepods of BC	Recreation Features Inventory
Reconnaissance 1:20,000 Fish & Fish Habitat Inventory Standards & Procedures (Version 1.1)	Recreation Opportunities Spectrum Inventory
Standards for Fish and Fish Habitat Maps (Version 2.0)	River Recreation
Ambient Freshwater & Effluent Sampling Manual	Visual Landscape Inventory Manual Procedures (Version 2.0)
Aquatic Biological Sampling Manual	Routes & Trails
Lake and Stream Bottom Sediment Sampling Manual	Caves
Standard Operating Procedures for Hydrometric Surveys	Wilderness Monitoring Sampling Plots
Guidelines for Designing & Implementing a Water Quality Monitoring Program in BC	Comprehensive Guidelines for Cultural Heritage Resource Inventories (Site Inventory Form & Recording Guide)
Guidelines for Interpreting Water Quality Data	Tourism Resource Inventory Standards & Procedures 1:250,000 Scale
Fisheries Information Summary System Data Compilation & Mapping Procedures	Traditional Use Site Database Technical Specifications
Automated Water Qulaity Monitoring	Culturally Modified Trees: (Handbook for ID & Recording of CMT's; Operational Procedures: Interim Permit Reporting & Recommended Report Format; Operational Criteria for Assessing Scientific & Cultural Significance of CMT's)
Atmosphere & Air Quality	**Earth Science**
Bibliography of Air Quality - British Columbia	
Bibliography of Meteorology & Climatology - British Columbia	Groundwater Mapping & Assessment in BC (Vol. I & Vol. II)
British Columbia Air Quality Monitoring Networks	Preliminary Seismic Microzonation Assessment for BC
Climatological, Meteorological & Air Quality Products Summary	BC Archaeological Impact Assessment Guidelines (includes Archaeological Site Inventory Form)
Description of British Columbia Meteorological Networks	Guidelines and Standards for Terrain Mapping in BC
	Specifications & Guidelines for Bedrock Mapping in BC
	Terrain Stability Mapping in BC: A Review & Suggested Methods for Landslide Hazard & Risk Mapping

Appendix 1 RIC—Standards

Land Use	
	Standards for Wildlife Radio Telemetry
Corporate Land Use Classification System for BC	Wolves & Cougars (Version 2.0)
Terrestrial Ecosystems -- Biodiversity	**Terrestrial Ecosystems -- Ecology**
Bats (Version 2.0)	Procedures for Environmental Monitoring in Range and Wildlife Habitat Management
Marbelled Murrelet	Soil Inventory Methods for BC
Plethodontid Salamanders	Standards for Terrestrial Ecosystems Mapping in BC (Ver 2)
Fast-stream Amphibians (Tailed Frogs & Pacific Giant Sal.)	BEC Subzone Variant Mapping
Forest & Grassland Songbirds	Field Manual for Describing Terrestrial Ecosystems in the Field
MacroFungi	BC Wildlife Habitat Rating Standards
Raptors	Standards for Broad Terrestrial Ecosystem Classification & Mapping for BC (Version 2.0)
Small Mammals (Shrews, Voles, Mice & Rats) Version 2.0	Terrain Classification System for BC (Manual 10 - Ver 2)
Aerial Based Inventory of Ungulates	Data Standards for Terrestrial Ecosystem Mapping in BC
Medium Territorial Carnivores (Coyote, Red Fox, Lynx, etc.)	
Pikas & Sciurids (Squirrels)	**Terrestrial Ecosystems -- Vegetation**
Woodpeckers	
Introduction to RIC Wildlife Inventory	VRI - BC Land Cover Classification Scheme (Version 2.0)
Pond-Breeding Amphibians & Painted Turtle (Version 2.0)	VRI - Photo Interpretation Procedures Phase 1 (Version 2.1)
Terrestrial Arthropods (Version 2.0)	VRI - Ground Sampling Procedures (Version 3.0)
Live Animal Capture & Handling Guidelines	VRI - Operational Field Procedures for Forest Resource Survey & Mapping Using GPS Technology
Shorebirds	VRI - Photo Estimation Retrofit Procedures
Upland Gamebirds	VRI - Quality Assurance Procedures for Photo Interpretation
Nighthawks & Poorwills (Goatsuckers)	VRI - Photo Interpretation Standards
Colonial-Nesting Freshwater Birds	Overview Aerial Survey Standards for BC & Yukon
Ground Based Census Techniques for Selected Cervids	
Riverine Birds (Dippers & Harlequins)	
Hares & Cottontails	
Snakes	
Swallows & Swifts	
Standard Taxonomy of BC Vertebrates	
Bears	
Other	**Standards under Development**
BC Standards, Specifications & Guidelines for Resource Surveys Using GPS Technology (Release 2.1)	Estuarine Mapping & Classification A20
LandData BC Corporate Data Model Framework	Nearshore Marine Habitat Inventory Manual
LandData BC Modelling Standards & Guidelines	Nearshore Marine Habitat Mapping Manual
RIC Map Projection Standards for Resource & Cultural Heritage Inventories in BC	General Biodiversity Inventory

Appendix 1 RIC—Standards

Standard for Developing Digital Data Specifications Standards Documents	Marten, Weasels & Fishers
	Standards for Voucher Collection and Preparation
	Wolverines
	Woodrat, Porcupine & Mountain Beaver
	Seabirds
	Waterfowl (Geese, Ducks & Sandhill Cranes)
	Beaver and Muskrat
	Moles & Pocket Gophers
	Bitterns & Rails
	Lizards & Skinks
	Rare Vascular & Non-vascular Plants
	River Otter & Mink
	Raccoons, Opossums & Skunks

Appendix 2 - RIC Training Courses

The following is a list of RIC Training courses that have either been completed or are currently under development.

Course Title	Duration
Level 2	
• Resources Inventory Skills	15 - 20 days
Level 3	
• Electrofishing – Crew Member	2 days
• Archaeological Inventory	10 days
• Culturally Modified Tree Inventory	7 days
Level 4	
• Fish Identification	2 days
• Introduction to RIC Wildlife Species Inventory	2 days
• Using GPS Technology	1 - 5 days
• Culturally Modified Tree Inventory	5 days
• Reconnaissance Level Field Stream Inventory	3 days
• Introduction 1:20,000 Fish & Fish Habitat	3 days
• Reconnaissance Level Stream Field Inventory	3 days
• Wildlife Habitat Capability & Suitability	4 days
• Terrestrial Ecosystem Mapping	5 days
• Vegetation Resources Inventory	13 days
• Marbled Murrelet Inventory	5 days
• Raptor Inventory	4 days
• Terrestrial Salamander Inventory	4 days
• Forest & Grassland Songbird Inventory	4 days
• Small Mammal Inventory	3 days
• Describing Ecosystems in the Field	5 days
• Visual Landscape Inventory	3 days
• Recreation Resource Features & ROS Inventory	3 days
• Net Volume Adjustment Factor Sampling	5 days
• Bat Inventory	5 days

Pros and Cons of Continuous Forest Inventory: Customer Perspectives

Andrew J. R. Gillespie

Abstract.—The USDA Forest Service has historically conducted forest inventory on a state-by-state cycle, producing relatively high precision snapshots of forest resources for a given state at 7- to 15-year intervals. We are now considering a change to a continuous inventory system where we would operate at reduced intensity simultaneously in all states every year. Advantages for customers include the continuous availability of data that are on average half a cycle old; access to data of a uniform age across administrative boundaries; increased opportunities for partnering with Forest Inventory and Analysis, including funding intensification or special studies; a permanent role in an ongoing inventory program; and increased program efficiency. Disadvantages include the elimination of the periodic higher precision inventory; a potential loss of credibility among end users; the risk of poor program service for states unable or unwilling to contribute to the program; and the possibility that the continuous approach will be more expensive than the periodic in some parts of the country.

The USDA Forest Service Forest Inventory and Analysis (FIA) program has, over the past 70 or so years, been the major source of state-level forest inventory information across the US. The program provides periodic information on status and trends on a variety of parameters describing forests and forest use: area and type of forest; structure and composition of forests in terms of species, sizes, and volume; rates of tree growth, mortality, and removals; patterns of ownership of forest lands; and information on harvest efficiency and product flows throughout the US. This information is of vital interest to numerous customers including managers, policymakers, business interests, academics, and other interested citizens.

FIA has historically conducted forest inventory on a state-by-state cycle. Under this model, an inventory staff would focus all of its resources on collecting data within a single state, as quickly as possible. Analysis and reporting for the state would proceed once the data collection was completed, while the data collecting staff moved on to the next state. The result has been a periodic, once-every-X-years state-level inventory based on a full measurement of existing plots, with X ranging from 7 to 18 or more years. This relatively high precision snapshot would be reasonably accurate when reported; but over the subsequent years, the snapshot would not necessarily accurately describe the current state of the system due to changes occurring after the time of data collection. In practice, the difference between the inventory report and the actual state of the ecosystem would be unknown until the next measurement time. Until recently there were seven FIA field locations supporting regional cycles in different parts of the country. Average cycles ranged from 5 to 8 years in the south, 11 to 15 years in the rest of the US.

This approach to forest inventory was generally satisfactory until the 1980's. During this time, the primary focus for analysis was within a state, and program budgets were sufficient to keep the inventory cycle (time between remeasurements in a given state) at an acceptable level. However, in recent years there has been growing customer dissatisfaction with the types and amounts of information being provided. Primary areas of concern include:

1. Excessively long inventory cycles (15+ years in parts of the US) that cause long periods of high uncertainty about the state of the forest resource;
2. Lack of consistency between different regional FIA programs, which hampers the ability to conduct analyses that span administrative units;
3. Reduction in the number of analyses that are published in a timely fashion, associated with the redirection of program resources away from analysis and towards data collection to reduce the cycle.

These concerns have been expressed in two reviews of the FIA program (Anonymous 1992, 1998). This has led FIA over the past 5 years to reassess the existing program and to seek ways of better addressing customer concerns. In addition, the Agricultural Research, Extension, and Education Reform Act of 1998 directs the FIA program to

---

Forest Inventory National Program Leader, USDA Forest Service, Washington, DC, USA.

make significant technical changes including (1) switch from a periodic to an annual (continuous) inventory approach that measures 20 percent of all plots in each state each year; (2) development of a core program that will be implemented consistently across the US forest lands, including national forests; and (3) production of complete state reports at 5-year intervals, looking back over the previous 20 years' worth of data.

FIA has been considering the possibility of an annual approach to forest inventory since 1992, when the North Central FIA unit began development of a prototype annual inventory system in Minnesota, in cooperation with the Minnesota Department of Natural Resources and the FIA research unit in Fort Collins, CO. This program, called AFIS (Annual Forest Inventory System), was designed to operate within existing budget constraints. Satellite imagery analysis was used to differentiate between plots that could be modeled rather than visited, and plots where sufficient change had taken place to warrant a field visit. By visiting a smaller set of plots annually, and leveraging that information with remotely sensed data and models, it was hoped that a state-level report could be produced at more frequent (4-year or less) intervals. Although not as precise as the report from a full inventory, the more frequent updates were expected to be more timely and hence more useful.

In 1996, the Southern FIA unit, in cooperation with a coalition of industry and state partners, began contemplating a similar experiment. They selected a simpler approach, simply dividing the existing set of field plots into five overlapping panels, with the intent of measuring one full panel each year so that each plot would be measured once every 5 years. Since the FIA unit was at that time funded for only a 7- or 8-year cycle, this approach would require additional sources of funds, either from the Forest Service or from partners. Due to the extreme interest and pressure on the FIA unit to address the cycle problem, they eventually opted to skip the pilot test phase and simply implement the annual approach in several southern states in 1997.

Other FIA units have until now been interested observers. However, recent legislation directs all FIA units to make the transition to an annual inventory system over the next 5 years. The law that gives this direction also greatly expands the FIA mission in other ways, requiring more data collection on a wider array of parameters, implementation of FIA where it presently does not exist (e.g., central Alaska), and increased analysis and reporting requirements. It is not clear if Congress will provide additional resources needed to accomplish all of this, and it is not clear what the FIA program will do if such resources are not provided.

PROS AND CONS OF THE CONTINUOUS INVENTORY APPROACH

Most of the discussion to date of advantages and disadvantages of the continuous approach has been from the technical, statistical perspective: how can we best produce continuously updated data, and how will a continuous inventory approach make life easier for FIA, the producers of that information? But little formal thought has been given to whether changing to a continuous approach will address the concerns of our dissatisfied customers. This paper attempts to look at the expected differences in program outputs from the perspective of the educated consumer of forest inventory data, so that consumers better understand the full implications—positive and negative—of the proposed changes to the strategic forest inventory program.

I have identified at least five areas related to movement to continuous inventory that are consistently of major concern to many FIA customers and partners. I will discuss pros and cons in each of these areas:

1. Information quality—how accurate and precise is the information?
2. Information utility—how useful is the information?
3. Opportunities for partnership—how will the change affect partners' abilities to participate actively in the program?
4. Program efficiency—does this approach deliver the best value for the taxpayers' dollar?
5. Risk—What new problems might this approach create for the customer?

Unless specified, I will assume for comparison that the continuous inventory approach in use is the simple systematic panel approach being implemented by the Southern FIA unit. This implies that a state has a total sample of n plots, each is assigned to exactly one of five panels so that each panel covers the entire state at approximately equal intensity, with approximately equal numbers of plots in each panel. Comparisons to the periodic inventory system will assume a 5-year periodic cycle.

Customers of FIA

The primary customers of the FIA program include:

1. State and national lawmakers who use FIA information when making and passing laws. They need nationally consistent and state-specific information, constantly updated, on a broad array of forest

ecosystem attributes for making laws. They need summaries and analyses of those data.

2. State foresters who use FIA data for developing policy proposals, communicating with their constituents, and planning economic development. They need state-specific, constantly updated information on a broad array of forest ecosystem attributes. They need access to elemental data, as well as summaries and analyses of those data.

3. Private industry and consultants who use FIA information for business planning. They need the most up-to-date information possible, consistent across space without regard for political or administrative boundaries, on a broad array of forest product attributes. They need access to elemental data, as well as summaries and analyses of those data.

4. Government and private research institutions who use FIA data as a basis for conducting their own research and analyses. They need reliable information on a broad array of forest ecosystem attributes, consistent across space without regard for political or administrative boundaries. They need access to elemental data (tree-level data), both current data as well as historical data.

5. Environmental organizations that use FIA data to monitor and assess the effects of public policies on land use. They need information on a broad array of forest ecosystem attributes, consistent across space without regard for political or administrative boundaries. They need access to summaries and analyses of those data, and are increasingly interested in access to elemental data allowing them to conduct their own analyses.

6. Media that use FIA data in preparing interesting reports and articles for their readers. They need current and historical information on a broad array of forest ecosystem attributes, generally summarized and analyzed along political boundaries, e.g., national-, state-, or county-level data. They appreciate information portrayed in a readily understood format, especially using charts and graphics.

7. Internal Forest Service officials who use FIA data in preparing a variety of internal reports including the Resource Planning Act (RPA) reports, and occasionally revising/updating forest plans. They need access to data summarized according to state and Forest Service organizational boundaries (Regions/Forest/District).

Information Quality

Both the periodic and the annual inventory approaches are assumed to be designed so that they provide unbiased estimates of some parameters of interest that describe a forest. However, the parameters estimated are not necessarily the same for each approach.

Under the periodic approach, the parameter estimates are assumed to describe the state of the forest at some specific point in time. This is not precisely correct, since data collection always spans some time interval and thus reflects some kind of average state during a period of time. For example, a large forested state such as Maine, Georgia, Minnesota, or Oregon may take up to 3 or more years for complete data collection under existing budgets. However, under the periodic approach, the inventory is generally assigned to the year in which the bulk of the data were collected.

Under the continuous inventory approach, there are several options for which parameters might be estimated. One could take the panel of n/5 plots and simply calculate the parameters of interest for the current year. This would result in estimates for parameters that truly are observations for the year in question. However, the small sample of n/5 would not yield estimates as precise as the full sample based on all n plots. The estimated standard error of the mean would be larger for the n/5 sample by a factor of (5 = roughly 2.24). This would affect all estimates of precision including confidence intervals about the mean.

A more powerful approach over time would be to use some kind of moving average, combining the latest observation for all n plots taken over the past 5 years. This would yield an estimate of a different parameter, the mean value over the past 5 years. This is not the same as the mean parameter in the present year. There are many different ways for combining estimates in time series. The expected precision for the mean over the past 5 years would tend to be higher than the estimate based on a single year observation of n/5 plots, but lower than the estimate based on all n plots measured in < 5 years.

The moving average approach would tend to mask dramatic annual changes in the value of the parameter of interest, and would tend to lag behind current changes in the state of the system. The advantage for the user of this information is that the continuous approach yields updated information each year, with the information having an average age of 2.5 years (half the length of the measurement cycle). This alternative might be preferable to a periodic approach on the same 5-year cycle, which also yields information that, over the average of the cycle, is 2.5 years old, but at any given moment might be as much as 5 years old. If it is more important to users to be sure that they will always have information that is no more than 2.5 years old, then the continuous approach is preferable. Alternately, if users need high precision information and can accept periodicity of 5 years between snapshots, then the periodic approach would be more efficient because it would provide that higher degree of precision at the same cost.

This analysis depends greatly on the length of the cycles involved. A user might accept a periodic high precision snapshot at 5-year intervals, but find that the same level of precision at 8- or 10-year intervals is unacceptable. In such a case, the annual approach would be preferable, assuming that the continuous approach maintained the 20 percent per year sample. However, the same forces that cause the lengthening of the periodic cycle from 5 to > 5 years will likely act to reduce the continuous sample fraction from 20 percent of all plots each year to < 20 percent. In such a case, it still may be preferable to have some recent information rather than relying on a database in which all information is outdated.

In summary, users who want continuous access to data that are relatively recent, but never quite current, will prefer the continuous approach, while users who can wait longer for more accurate data will prefer the periodic approach. The preference for a continuous approach to inventory will likely be greatest for systems where the rate of change is greatest. For relatively stable systems, a periodic approach is probably more efficient.

Information Utility

It is necessary, but not sufficient, for information to be accurate and precise in order to be useful. Regardless of how accurate the data are, the information will not be useful if the ultimate consumers of the information do not believe in the reliability of the information. Accurate information presented in a manner that undermines its own credibility is not useful. With the periodic approach to inventory, we have maximum precision at fixed intervals. We can say with confidence that the data reflect observations of a trend at fixed points in time, and that changes that occur between the points are reflected with some accuracy in the periodic observations.

A drawback to the continuous inventory approach is that the lower precision inherent in the estimates based on 5 years of data will likely yield annual estimates that fluctuate more due to random error than do the estimates from the periodic inventory. This is an unfair comparison, because the true uncertainty of the estimates between years under the periodic approach is unknowable, since there are no data. However, the act of reporting updated estimates on an annual basis will inevitably invite comparison of the present estimates to those of previous years, and will cause consternation and distrust if there is deemed to be a significant variation from year to year. While statistically understandable, such behavior could nonetheless cause end users unfamiliar with technical issues to mistrust and doubt the results. This could result in good data that no one believes. This is more of a risk under the annual approach than under the periodic, where the lack of midcycle data prevents users from making the same comparison.

Increasingly, users are interested in analyzing data that span more than one administrative unit, i.e., more than one state. Under the periodic approach, each state inventory is conducted in sequence within a given region. This implies that adjacent states may have inventories that are years out of step. This presents an additional hurdle to the analyst who wants to combine data across a region. Typically all data must be somehow brought to a common year, generally by modeling or making some other assumption. This adds a component of uncertainty to the analysis—a component that is rarely quantified. The ultimate example of this problem presently occurs at 5-year intervals when the Forest Service prepares its Resource Planning Act report, when data for all 50 states, spanning some 15 years, must be updated to a common year.

The continuous approach would eliminate this problem. Data would be available for all states each year, so could be treated similarly without having to update some states to a reference year. There could be some added complexity if adjoining states had different sampling fractions (say 10 percent in one state and 20 percent in the next). However, the existence of annual data for all states would greatly simplify the task of updating or otherwise standardizing data to a common point in time.

In summary, the continuous approach to inventory will yield information that fluctuates from year to year and that may cause concern or lack of confidence in some end users. The periodic approach avoids this problem by not reporting information year to year. Data from the continuous approach will be much easier to analyze across administrative boundaries such as states or FIA units.

Partnerships

FIA is increasingly relying on and welcoming partnerships in accomplishing the FIA mission. For purposes of this paper, "partnership" is defined as a relationship in which two or more parties share in the costs of completing work. State forestry agencies in particular are frequently establishing partnerships with FIA through the contribution of office space, staff time, vehicles, and other resources that allow the FIA work to proceed at a faster pace. Historically, many states have contributed resources to FIA for collecting additional data beyond the base program—for example, to intensify the plot network or to collect special interest variables on some or all plots. In the southern part of the US, several states are using their own resources to hire staff for field data collection for the base set plots.

Under the periodic inventory approach, it was often difficult for partners to participate in the FIA program. The long time between subsequent inventory activities made it impossible to support a permanent staff specifically for collaborating with the FIA unit. Normal employee turnover tended over time to reduce the staff familiar with the FIA program, methods, and opportunities. Additionally, partners who wanted to seek resources to invest in FIA—either to speed up the base program or to buy additional information—were often at a disadvantage because of the timing. For example, a state forester might have to ask his/her legislature for a relatively large sum of funds that might not be available in the year needed. The periodic nature of past inventory programs often led to periodicity in relationships between FIA partners, resulting in a program that was forever locked in a less productive "still-getting-to-know-you" kind of relationship.

The continuous approach offers the opportunity to grow those relationships to maturity. Since there will be operations in every state every year, FIA and partner staff will have constant contact, creating a chance to build long-term working relationships. Partners wanting to contribute to the program will be able to seek permanent budget allocations and staff to do so, at a lower annual cost. The existence of annual field work in each state means that partners now have the opportunity in any given year to inject additional resources into the program for collecting additional data about some issue relevant to their needs, without having to wait years until the next inventory for their state. For organizations looking to increase their involvement in FIA, the continuous approach to inventory is clearly preferable to the periodic approach.

What about states that are not able or willing to contribute resources to support the FIA program? It is less clear that the continuous approach is superior for them. For example, it is unlikely that FIA will be able to conduct an annual inventory in some states and a periodic one in others; the overhead burden would be too expensive. FIA resources will likely be spread across all parts of the country to provide some consistent base continuous program to everyone, but the resulting program may not be at the annual intensity desired by customers. There is a risk that states that are unable to add additional resources may be asked to settle for a lower intensity annual inventory program that may actually be less usable than the former periodic inventory. States that can't or won't contribute to implementing the FIA mission may be better off under a periodic system.

Program Efficiency

Customers are interested in program efficiency because ultimately they are paying for the program through tax dollars. If FIA can maximize its efficiency, customers will have to spend less cash and less political coin to get the resources needed to complete the work. Changing to an annual inventory program will change some of the efficiencies of the program, but it is not yet clear if the total change is a net loss or gain.

One immediate opportunity to increase efficiency is through the merger of the FIA program with the field plot portion of the Forest Health Monitoring (FHM). At present FHM is a related program that collects data on forest health parameters in all implemented states on an annual basis. There is some redundancy between the programs: for example, FHM collects a set of mensurational data that is largely duplicated on FIA plots, and it involves many of the same management and supervisory staff that also manage FIA. The biggest obstacle presently to integrating these programs is the fact that FHM needs annual data in each state during a 10-week measurement window in the summer, while FIA remains a periodic program in most states. Once FIA changes to an annual approach, it will be very easy to simply designate a subset of the annual FIA panel of plots as dual FHM plots, and measure these once with a combined crew. In addition to being more cost effective, this will reduce the likelihood of multiple visits to the same plot that might annoy private landowners. This will also provide maximal linkage between the two databases, strengthening joint analyses. Since many states are partners in both FIA and FHM, combining these programs will enable states to reduce some overhead associated with participation.

It is not clear at this time how field logistics will be impacted by a change to a continuous inventory. In places where fieldwork can be done year round, such as the southern US, there may be gains in efficiency associated with permanently locating field staff in working circles wherein they can do most of their annual plots with minimal overnight travel. This contributes to a stable workforce, which may reduce turnover and will require less training (albeit more salary) over time.

The situation becomes more complicated in less accessible areas where the working field season is shorter. It will not be cost effective to permanently station employees in areas with short field seasons. Crews will have to follow annual migration patterns, with southern "winter grounds" and northern "summer grounds." In such areas, increased travel costs associated with the need to cover all states each year may make continuous inventory more expensive than a similar cycle periodic inventory.

The continuous approach is more efficient from the perspective of reporting. Both periodic and continuous approaches offer the same basic, comprehensive reports at fixed intervals. However, the continuous approach offers the opportunity for additional reports to reflect events that may occur between major reports. For example, each year in the US, there are some events that have dramatic impacts on forests: flooding along the Mississippi, ice storms in New England, and fires in Florida are three recent examples. A continuous approach would enable analysis and reporting on the effects of the event without having to commission or fund a special study. Any additional resources could be used more efficiently by building on the planned annual program. The continuous approach provides a constant platform for responding to unpredictable events.

Risks

Any major change has risks associated with it. It is unlikely that change to a continuous inventory will not have any downside or even that we will anticipate all of the advantages and disadvantages of such an approach. In addition to the risks already discussed above, a few more are worth noting here. All these risks should be weighed against the risk of doing nothing to the current program, which may accelerate the erosion of support for FIA as FIA meets the needs of fewer and fewer customers.

One risk is that changing to an annual inventory system may tend to favor "important" states at the expense of "unimportant" ones. There are various definitions of what constitutes "importance:" area of forest, rates of harvesting, species richness, recreation use, political clout, and proximity to population have all been used at one time or another to justify the need for increased information gathering. Since it is unlikely that FIA will be given all of the resources needed to fully implement the program called for by Congress, some choices will have to be made about resource allocation. This is not an inherent property of the continuous inventory per se, but rather an artifact of the change taking place. The change presents an opportunity to assess present and future resource allocation. States from areas deemed in the past to be "less important" need to participate in the present process of evolution to ensure that their needs are also heard.

A second risk inherent in the continuous inventory approach is that the linkage between funding, cycle, and information quality becomes less obvious. Historically, funding for FIA has tended to follow a pattern of slow declines (in real terms) over some time period, followed by sudden increases reflecting political support from customers dissatisfied with program delivery. Under the periodic approach, the gradual reduction in funding led inexorably to an increase in the cycle: if an FIA unit could only afford 11 field crews rather than 15 crews, State X would take 3 years instead of 2 years to complete. Eventually, cycles would get so long that customers would mobilize their political representation to provide a correcting influx of funds. It is relatively easy for customers to monitor the cycle length, and thus to activate a political response when the cycle becomes too long.

However, degradation under a continuous inventory system may be subtler. If circumstances change, a unit reducing from 15 to 11 crews would still measure a certain number of plots in each state each year, but it might be 17 percent rather than 20 percent. The unit could still produce an annual database, and reports at 5-year intervals that are based on 85 percent new data and 15 percent old data. The information products could still be delivered on time, but they would be of slightly lower usefulness. It seems to me that this kind of degradation would be more insidious, less obvious, and less easy to address through the raising of political awareness. A continuous approach might thus allow itself to degrade farther before being fixed. On the plus side, since everyone directly benefits in the first year following a correcting increase in funds, it may be easier to mobilize political support under a continuous system once the problem is recognized.

The third risk is that the entire debate about changing to the annual inventory approach is not a solution to the problems with the present inventory program as much as it is a classical example of a work avoidance mechanism. Heifetz (1994) outlined a theory about how individuals and organizations react to stress caused by serious problems. Rather than confronting and fixing the underlying problems, it is often easier to make some cosmetic change that gives the appearance of dealing with the problem. This is often sufficient to convince people that Something is Being Done, so the stress level subsides—for awhile. This cycle can be repeated endlessly, since the players on both sides tend to change over time. The distinction that Heifetz makes between adaptive work aimed at fixing problems, and work avoidance is simple: if the action reduces stress but does not solve the problem, it is work avoidance. If it solves the problem—even at the expense of raising or maintaining stress—then it is adaptive work.

Changing to a continuous inventory simply means changing the order in which we measure our existing set of plots. This by itself will not solve the problem of excessive cycle lengths—it will simply redistribute the problem. If all we do is mandate a change to an annual inventory, we may reduce the stress for a few years, but it will eventually catch back up with us. A continuous inventory may have some advantages, but will not by itself solve the major problems plaguing FIA.

There are opportunities for making additional changes that will address the problem. We might reduce overall program costs and enable ourselves to reduce cycles within current budgets by substituting technology such as satellite image analysis for field visits, as is being explored in Minnesota. Alternately, we can increase the resources allocated to FIA by seeking increased federal appropriations and/or by leveraging additional support from other partners. This is the approach being taken in the south, where states are contributing significant resources to attain what is in effect a 5-year cycle. In both cases, it is worth noting that it is not the simple fact of the continuous inventory approach that is solving the problems, it is the change to a continuous system combined with other major programmatic changes. Customers of FIA need to keep this in mind: the advantages or disadvantages of the change to a continuous inventory must be considered simultaneously with other necessary program changes.

CONCLUSIONS

The FIA program is undergoing a period of major change in response to the concerns and needs of our customers. One of the major changes underway is the shift from periodic to continuous forest inventory in each state. Advantages of such an approach for our customers include the continuous availability of data that are on average half a cycle old; access to data of a uniform age across administrative boundaries; increased opportunities for partnering with FIA, including funding intensification or special studies; a permanent role in an ongoing inventory program; increased program efficiency through integration with the Forest Health Monitoring program; and more flexible opportunities for reporting, especially in response to unexpected events.

Disadvantages include the elimination of the periodic higher precision inventory; a loss of credibility among end users who do not understand why annual estimates fluctuate; the risk of poor program service for states unable or unwilling to contribute to the program; and the possibility that the continuous approach will be more expensive than the periodic in some parts of the country.

In addition, there are risks: the risk of some states being left out because their forest resources are deemed "unimportant;" the risk that future degradation of FIA information quality will be harder to detect; and the risk that excessive focus on the issue of periodic vs. continuous inventory will avoid the real work of dealing with issues such as consistency, funding, and equity in program delivery.

The change to an annual inventory program offers us the opportunity to simultaneously make other key changes that are needed to improve the FIA program. We must look carefully and equally at all aspects of the program in determining where we want to be and how best to get there. It appears that the political momentum has already decided that FIA will move to a continuous approach for the next generation of fieldwork; technical considerations have become secondary. Nonetheless, I believe that transition to a continuous inventory system, if made simultaneously with other critical changes in the FIA program, will in the long run be in the best interest of the largest number of FIA customers. If we can simultaneously address the existing problems of inconsistency in methods, incompleteness in coverage, and inadequate resources to deliver the required level of information, then we will be able to create an FIA program that will deliver useful information for many years to come.

ACKNOWLEDGMENTS

This paper was reviewed by Dr. Paul Van Deusen, Department of Civil Engineering, Tufts University, Medford, MA, USA; and Dr. Jeff Goebel, USDA Natural Resources Conservation Service, Washington, DC, USA.

LITERATURE CITED

Anonymous. 1992. The report of the First Blue Ribbon Panel on Forest Inventory and Analysis. Washington, DC: American Forest & Paper Association. 15 p.

Anonymous. 1998. The report of the Second Blue Ribbon Panel on Forest Inventory and Analysis. Washington, DC: American Forest & Paper Association. 17 p.

Heifetz, R.A. 1994. Leadership without easy answers. Cambridge, MA: Harvard University Press. 348 p.

Selection of Plot Remeasurement in an Annual Inventory

Mark H. Hansen, Hans T. Schreuder, and Dave Heinzen

Abstract.—A plot selection approach is proposed based on experience from the Annual Forest Inventory System (AFIS) in the Aspen-Birch Unit of northestern Minnesota. The emphasis is on a mixture of strategies. Although the Agricultural Act of 1998 requires that a fixed 20 percent of plots be measured each year in each state, sooner or later we will need to vary the scheme to accommodate pressing user needs and budget constraints while still preserving the integrity of the annualized cycle. Differing probabilities of selection will need to be accommodated; variance and confidence interval estimation can be done using bootstrap methods.

Under this different approach, the existing ground plot locations will all be remeasured periodically, but not following the regular 5-year cycle of 20 percent each year. A certain percentage of plots, say 10 percent of the currently installed grid, would be selected annually, so that all plots would be remeasured at least once over a 10-year period. In addition, Forest Health Monitoring (FHM) plots (about 2 percent of the existing locations) would be measured every 4 years, and another percentage, say an additional 10 percent, would concentrate on parts of the population of particular interest. For example, we might focus on plots more useful for annual forest area change estimation by selecting plots that are more likely to change to or from forest or select other plots that will be of greater value in improving plot predictions obtained from models. We use the term model in the broadest sense of small area estimation (includes multiple imputation, plot, and tree models to update individual plots or to predict for every ha in the population of interest). Alternatively, additional ground plots could be measured to assess annual acreage changes in selected areas.

Because of special needs, some plots might be measured several times in a 10-year cycle, really complicating the probabilities of selection for these plots. Typically, an approximately equal number of plots are measured each year, but under the strategy presented here we would have flexibility to accommodate funding or user-need changes.

The Minnesota Department of Natural Resources and the Forest Inventory and Analysis (FIA) Units of the North Central (NCFIA) and Rocky Mountain Research Stations cooperated on a project to test and implement an Annual Forest Inventory System (AFIS) in Minnesota. The purpose of this study was to develop a system to replace the 8- to 15-year periodic inventories conducted by the USDA Forest Service with a system through which plots are measured every year and estimates of the forest resources can be made annually. The AFIS system incorporates the previous set of plots and remeasures a portion at various times. Components of AFIS are: a tree-level forest growth simulator to update tree and plot measurement data on an annual basis, satellite imagery examined every 4 years to determine the extent and location of major changes in vegetation over time, and a system to select plots for measurement each year.

The Farm Bill of 1998 (U.S. Senate Bill 1150, Agricultural Research, Extension, and Education Reform Act of 1998) mandated that 20 percent of all plots be measured in each state each year. This percentage is likely to be reduced because of cost considerations. We have learned valuable lessons that will be helpful in planning intelligent plot selection for use in the future when a certain percentage of plots will be done in each state, but in many instances there will be a need to select additional plots and/or to modify the period between measurements. The purpose of this paper is to discuss the rationale used in the planned development of the plot selection method in AFIS prior to the Farm Bill of 1998 and to discuss how sample selection in annualized inventories can be modified to accommodate future needs based on our experience with AFIS.

Biometritian, Forest Inventory and Analysis Program, North Central Research Station, St. Paul, MN, USA; Mathematical Statistician, Forest Inventory and Monitoring Environmentrics Project, Rocky Mountain Research Station, Fort Collins, CO, USA; and Supervisor, Forest Resources Assessment and Inventory Unit, Minnesota Department of Natural Resources, Grand Rapids, MN, USA, respectively.

REVIEW OF LITERATURE

The sampling design used by NCFIA prior to the Farm Bill of 1998 was presented in Hansen (1990). This design is basically sampling with partial replacement (SPR) with the addition of a growth model and stratification for change. The three components required by the design were:

1. A set of remeasurable ground observation plots,
2. A growth model capable of updating these old plot data to the current date, and
3. A method for identifying change plots, i.e., those plots that the model is not capable of updating.

The sample design was simple in that the old plots were first stratified into two classes, changed and unchanged. The changed plots were treated separately in that traditional continuous forest inventory estimators were used (Schreuder *et al.* 1993). All unchanged plots were updated to the inventory date using the growth model. In addition, some unchanged plots were remeasured. These remeasured unchanged plots can be used to see how well the growth model works, i.e., how closely the updated, projected data match actual remeasurement data.

New plots were also added to improve the estimates and to ensure that the next survey had enough plots available for remeasurement or projection in the next inventory. As in SPR, new plots may only be necessary if the accuracies desired for estimates of volume and growth dictate that it is most efficient to add new plots, or if the time between the past and current surveys is so long that lost plots are a problem.

The STEMS growth model updated the unchanged plots (Hansen 1990). This distance-independent individual tree growth model was used because it is still the best system available for the type of data NCFIA collects. Any growth model that can produce estimates of the variables of interest from old plot data could be used. Improved models are now being developed (McRoberts 2000).

The system initially used change identified on current aerial photographs (scale:1/15,840) but then shifted to Landsat Thematic Mapper data. The sampling scheme produced a tree list for at least two points in time for all plots. These tree lists were then entered as individual observations of the plot in the NCFIA database. One important feature of the estimation process was that although all plots contribute to the estimates of area, volume, and growth, only the remeasured plots are used to estimate removals. However, this smaller sample is concentrated in the change strata, where the majority of the removals are found.

MANUAL AND DIGITAL CHANGE DETECTION

Landsat Thematic Mapper (TM) scenes were purchased on a regular 4-year interval to obtain imagery of Minnesota. All data were purchased from Earth Observation Satellite Company (EOSAT) of Lanham, MD.

The initial change stratification for AFIS was done manually only for the sample plot locations. Each plot was located on both the 1986 and 1990/91 TM imagery, and the vegetative cover of the two images at the plot location was observed. The plot was classified into one of five change-in-vegetative-cover classes (major increase, minor increase, no change, minor decrease, major decrease). We estimate the area within each change stratum based on these samples and treat these estimated strata sizes as known for estimation purposes.

Digital change detection is now being done on a pixel-by-pixel basis in Minnesota, which yields complete stratification of the population. Plots with considerable harvesting and mortality can be detected. This classification is based on the differencing (1990/91 value minus 1986 value) of three TM bands (3, 4, and 5) and a five-by-five pixel averaging of the combined differences. With digital change detection, strata sizes can be based on complete coverage using all pixels.

DESCRIPTION OF THE ASPEN-BIRCH UNIT

Kingsley (1992) noted that the Aspen-Birch Unit consists of five counties in extreme northeastern Minnesota, the most heavily forested area of the state. Today the unit is generally dominated by hardwoods, especially by aspen. The unit consists of 8.7 million acres of land, of which 7.4 million acres are forested; Cook and Lake Counties are more than 90 percent forested (see figure 1). Table 1, a condensed version of a table in Kingsley (1992), summarizes key information for the unit after the 1990 survey.

Table 1.—*Selected forest statistical information for the Aspen-Birch Unit*

Description	Total	Standard error (% of the total)
Growing-stock volume (1990) (million ft^3)	5,608.3	1.08
Growing-stock growth (1977-89)(million ft^3/yr)	132.1	1.88
Timberland area (1990) (thousand acres)	5,878.7	0.57

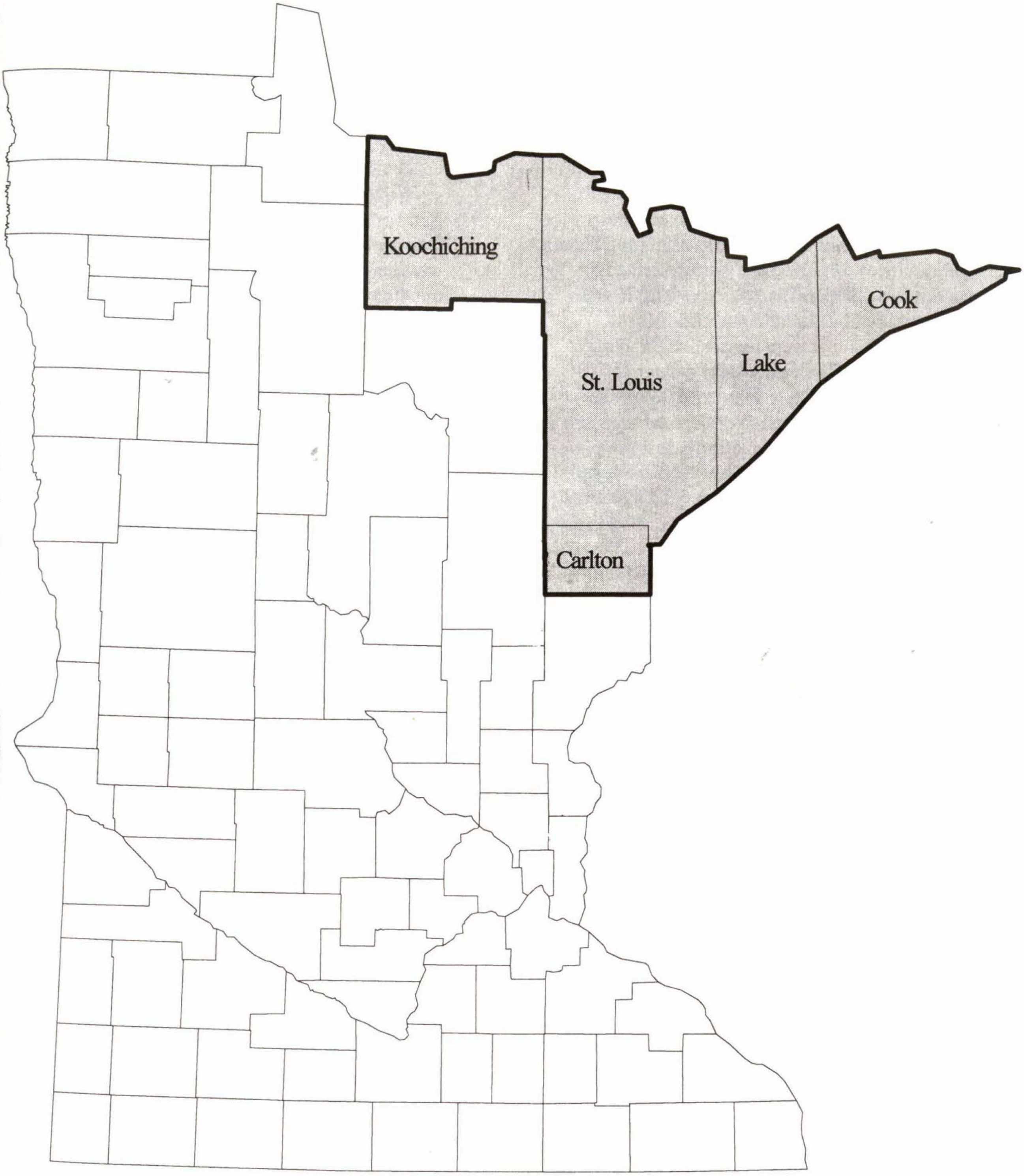

Koochiching
St. Louis
Lake
Cook
Carlton

Figure 1.—*The Aspen-Birch Unit, Minnesota.*

The unit has a strongly fiber-oriented forest economy. The area has a mixture of timberland owners (23 percent state, 22 percent federal, 21 percent county, 15 percent private individuals, 8 percent forest industry, and 11 percent other private) and a wide range of upland and lowland forest types. The area of sawtimber-size stands increased 476,200 acres from 1977 to 1990, although poletimber and seedling-sapling stands still dominate.

The 1977 inventory was the fourth FIA inventory in Minnesota and consisted of an entirely new sample. The methods and results of this inventory were described by Spencer and Ostrom (1979). The three previous inventories used different methods and did not establish any permanent sample plots that were remeasured in this inventory. In the Aspen-Birch Unit, this inventory consisted of (1) a phase 1 sample of over 36,000 photo plots that were used for stratification of the total area into aerial photo classes and (2) a systematic phase 2 sample of 5,099 plots. These plot locations were the base sample used for the 1990 (fifth) inventory that used the methodology described above.

INITIAL PLOT SELECTION CRITERIA

AFIS was first implemented in 1992, 2 years after the 1990 (fifth) periodic inventory of the area was completed. At that time we began selecting plots for remeasurement. The first year of AFIS continues with this same system of numbering inventory cycles and is referred to as the sixth cycle. Each additional year of AFIS is another cycle. There were several objectives in the development of the initial implementation of the plot selection methodology of AFIS, including:

1) Identify and remeasure the strata containing disturbed plots more intensively than strata containing undisturbed plots. Disturbed plots are basically plots where forest conditions have changed drastically due to outside events such as harvesting, stand treatment, and catastrophic mortality that go beyond changes that growth models such as STEMS can predict.

2) Remeasure a percentage of undisturbed plots to test and adjust the STEMS model for current conditions that may differ from those that existed when STEMS was originally calibrated. Methods to adjust the STEMS model for local conditions have been used extensively by NCFIA (Smith 1983), and these methods correct the regional model to conditions that are unique to the region and time period where additional remeasurement data exist.

3) Remeasure or drop each plot before it is so old that remeasurement is difficult. This is to ensure that plots are not lost and dropped out of the system. Plots become increasingly more difficult to locate as time since last visit increases. The cost of remeasurement and the probability of lost data both increase over time.

4) Remeasure some undisturbed plots more frequently. Year-to-year changes in weather can influence growth and mortality, and models should be recalibrated to account for changes in growth due to these effects. These measurements could also be used to help estimate the error in predictions of growth both from the growth model (prediction errors) and from remeasurement data (measurement errors).

5) Stabilize the number of plots that are measured each year to avoid year-to-year changes in budgets needed for plot measurements. Under the current periodic inventories, the number of plots measured in a state changes drastically from year to year.

6) Maintain the existing core set of permanent plots as much as possible.

7) Ensure a probabilistic sample every year. This ensures that sample-based estimates of population parameters can always be made.

Based on these criteria, the following plot selection algorithm was developed for the first 4 years (1992, 1993, 1994, and 1995) of AFIS in the Apen-Birch Unit of Minnesota.

1) In 1992, plots were selected using a systematic sample with a random start of the existing plot locations (originally established as a systematic sample) in the Aspen-Birch Unit since the disturbance information was not available at the time 1992 field work began. No priority was given to plots based on the time since last measurement. The plots measured in the 1990 inventory have the same probability of selection as plots measured in the 1976 inventory, found to be undisturbed in 1990, and not selected for remeasurement in 1990.

2) In 1993 to 1995, one-third of the plots identified as disturbed by the manual disturbance classification were selected for remeasurement. For each disturbed plot, a measurement year (1993, 1994, or 1995) was assigned using a random number generator.

3) In 1993 to 1995, a sample of 1/20th of undisturbed plots were selected for remeasurement with the probability of selection proportional to the number of years since the plot had last been measured. This method gave higher selection probabilities to plots that had not been measured recently and allowed for some plots to be measured on a more frequent basis.

Table 2 shows the numbers of plots that were selected in each inventory starting with the 1977 periodic inventory. This table accounts for all plots. Most of the nonforest without trees plots are not visited by a field crew. These plot locations are identified on aerial photographs during each inventory to verify that they are still nonforest plots and are primarily water, marsh, and agricultural lands that are easily identified as nonforest on aerial photos.

As indicated, for example, in Schreuder and Wardle (1999), the database will be or will become the main product of these annualized inventories. Because of this and increased sophistication in users, we expect the following objectives:

1) For annual estimates of totals and rate of change, use areas of sufficient size to have an adequate sample.

2) Assess annual changes in acreage for major cover types. Assess annual changes in volume by species by the four regions in Minnesota, such as aspen/birch, northern pine, central hardwood, and prairie, (hardwood sawtimber, black spruce stands, conifer stands, aspen/birch acreage).

3) Meet FHM (forest health monitoring) needs.

4) Identify areas with high unexpected disturbance for which a "quick" followup example is desired, either by ground plots or very low altitude photo plots.

5) Test and verify models.

6) Asses land-use change.

CONTINUATION OF PLOT SELECTION IN ASPEN-BIRCH UNIT

Data from the first 4 years of AFIS have yielded observations of the disturbance rates that have occurred in this unit. Over the nominal 4-year time period (1986 to 1990/1991) of manual TM disturbance detection, an overall disturbance rate of approximately 3.0 percent per year (592 disturbed forest plots from a total of 4,880 forest plots over 4 years) was observed. This disturbance can be broken down into two groups:

a) Plots that had been classified as disturbed between the 1977 and 1990 inventories.

b) Plots that had been classified as undisturbed between the 1977 ans 1990 inventories.

The annual disturbance rates in the a and b groups was 1.1 percent and 3.2 percent, respectively. Based on these observed disturbance rates, we developed a function that we use in our projection to simulate the probability that a plot will be classified as disturbed based on the number of years since the plot was last measured. This function is flat for the first 4 years and then increases linearly after that. A number of plots were considered disturbed in two consecutive 4-year TM cycles. As we visited these plots in the field, it became apparent why. The first classification was often due to a decrease in the canopy (caused by harvesting, fire, or some other event), and the second disturbance was often an increase in canopy related to the regeneration of the plots. It was inefficient to remeasure these plots for the second disturbance. Usually the condition of plot regeneration could not be characterized yet. The first measurement provided the needed information on removals and mortality and often gave as good an estimate of regeneration as a second remeasurement 1 to 4 years later. We decided that if a plot was classified as disturbed in two consecutive 4-year TM cycles, the first measurement data would be examined, and if the plot had been harvested in the first measurement, we would not remeasure the plot in the second 4-year TM cycle. Instead, we used the growth model to project these plots for another 4 years but still included them in the disturbed strata. These plots are typically clearcut, and a 4-year projection simply moves them from a 1- to 3-year-old seedling/sapling stand to a 5- to 7-year-old seedling-sapling stand, neither of which would contain merchantable volume. Unless we find that the observed disturbance on these plots is of considerable interest for other reasons, they may not be measured again possibly until they become well-established poletimber stands, most likely at about age 15-20.

Table 3 shows the expected number of plots to be measured in the Aspen-Birch Unit for each cycle (year) of

Table 2.—*Number of plots selected in FIA inventory cycles 4 to 9 by type of plot and ground classification, Minnesota, Aspen-Birch Unit*

			Type of plot			
Inventory cycle and ground classification	**Total number of plots**	**New or replacement plots**	**Undisturbed plots remeasured**	**Disturbed plots remeasured**	**Undisturbed plots projected**	**Disturbed plots projected**
Cycle 4 - 1977						
Timberland	3,275	3,275	0	0	0	0
Other forest	620	620	0	0	0	0
Nonforest with trees	40	40	0	0	0	0
Nonforest without trees	1,164	1,164	0	0	0	0
TOTAL	5,099	5,099	0	0	0	0
Cycle 5 - 1990						
Timberland	4,880	1,452	900	1,689	839	0
Other forest	1,012	620	51	37	285	19
Nonforest with trees	49	13	18	16	2	0
Nonforest without trees	1,566	463	373	140	575	15
Lost/denied access	140	0	3	136	1	0
TOTAL	7,647	2,548	1,345	2,018	1,702	34
Cycle 6 - 1992						
Timberland	4,870	2	304	66	3,694	804
Other forest	1,013	0	87	2	891	33
Nonforest with trees	54	0	6	0	40	8
Nonforest without trees	1,568	0	122	10	1,340	96
Lost/denied access	4	0	3	1	0	0
TOTAL	7,509	2	522	79	5,965	941
Cycle 7 - 1993						
Timberland	4,860	1	109	254	3,887	609
Other forest	1,015	0	3	0	977	35
Nonforest with trees	56	0	1	2	45	8
Nonforest without trees	1,573	0	1	4	1,462	106
Lost/denied access	2	0	0	2	0	0
TOTAL	7,506	1	114	262	6,371	758
Cycle 8 - 1994						
Timberland	4,853	0	83	248	3,913	609
Other forest	1,016	0	25	15	955	21
Nonforest with trees	57	0	0	3	46	8
Nonforest without trees	1,577	0	31	31	1,433	82
Lost/denied access	1	0	0	1	0	0
TOTAL	7,504	0	139	298	6,347	720
Cycle 9 - 1995						
Timberland	4,854	0	76	289	3,920	569
Other forest	1,016	0	21	11	959	25
Nonforest with trees	57	0	1	5	45	6
Nonforest without trees	1,576	0	34	36	1,430	76
Lost/denied access	0	0	0	0	0	0
TOTAL	7,503	0	132	341	6,354	676

AFIS by the number of years since last remeasurement. The numbers here are a total of the timberland, other forest and nonforest with trees land-use classes, the plots that require field crew visits. Plots without trees are not included in this and following tables because they do not require field crew measurements, typically the major cost of the inventory. These numbers are based on a slight modification of our original plot selection criteria, assuming a disturbance rate that is constant for each cycle. The modified plot selection criteria are as follows:

1) Disturbance detection will be done every 2 years. This disturbance information will be available at the start of cycle 10, 14, 18, ... measurement periods.

2) Any plot identified as disturbed will be remeasured in one of the next 4 years after disturbance has been observed.

3) The total number of plots to be measured each year will be held to a constant, desired total number of field plots (n_t).

4) Once the disturbed plots have been identified (n_d), n_u ($= n_t - n_d$) plots will be selected from the undisturbed plots by giving highest priority to those with the longest time since last remeasurement. That is, no undisturbed plots that were measured in the 1990 inventory will be remeasured until all the undisturbed plots from 1977 have been remeasured. Similarly, as we move ahead into future years of AFIS and all the 1977 plots have been remeasured, no undisturbed plot that was last measured in the nth cycle will be remeasured if undisturbed plots from the (n-1) th cycle have not been remeasured.

As can be seen in table 3, a few (26) plots will go 22 years between remeasurement in the year 1999; however, in 2008 there are 225 plots that will go 18 years between remeasurement, and then the system stabilizes and no plot goes more than 17 years without remeasurement. The probabilities of selecting each plot will be kept track of carefully and in some cases will have to be 1 in a certain year. After the year 2012, the distribution of plots by years since last measurement stabilizes. These projections assume that the disturbance rate does not change and that over time we continue to sample the same number of plots each year. The effect that changes to these assumptions can have on the number of plots selected can be seen in tables 4 and 5.

Table 4 presents a second estimate of the plots to be measured over a number of cycles of AFIS using the same for remeasurement is clearly apparent when you compare tables 3 and 4. In this scenario, it takes longer (2016) for things to stabilize. Once a stable state is reached, plots can go 21 years without remeasurement, but fewer plots reach this maximum.

The reasons for these differences are clear. In both cases we are measuring the same number of plots each year. With a higher disturbance rate, more resources must go into measuring the disturbed plots (at less than the maximum interval) thus requiring this maximum interval to increase. If there was no disturbance, the system would stabilize at a maximum remeasurement period of N_t/n_t years where N_t is the total number of plots available for remeasurement.

Table 5 shows how this plot selection method responds to changes in the disturbance rate. We start with the disturbance rate used in table 3, but change detection done in 2000 and 2004 assumes the much higher rates of disturbance that we used in table 4. After 2004, we again go back to the original disturbance rate. This fluctuating disturbance rate is similar to what would happen when a major short-term disturbance such as a wind storm, a temporary increase in harvesting, or a period of drought causes high mortality. Note how the change in disturbance modifies the age of the plots selected for remeasurement for a while; however, after the original disturbance rate returns, the system eventually reaches the same stable state it has in table 3.

In this scenario, once the system has reached stability, only disturbed plots would have a remeasurement period less than the maximum period set. This selection method meets all of our original criteria for plot selection except for criterion 4: remeasure some undisturbed plots more frequently. This original criterion was designed to provide a data set to help estimate and calibrate the growth model for changes in weather or other factors. The original plot selection method of remeasuring undisturbed plots with probability proportional to the number of years since last measurement did provide undisturbed plots with various remeasurement periods. But these plots did not really meet the objective for which the criterion was designed. For estimation and modeling of short-term changes in growth and mortality, what is needed is a set of sample plots that continue to be remeasured on a regular short-term basis. Under our original plan, an undisturbed plot may be measured in 2 consecutive years and then not remeasured again for 20 years. After we initially developed the AFIS plot selection criteria, the Forest Health Monitoring program (FHM) was implemented in Minnesota. FHM plots, a systematic sample of 325 forest plots across Minnesota (83 in the Aspen-Birch Unit), are now being measured on a rotating basis every 4 years and can be used for calibration of growth and mortality models to account for

Table 3.—*Total number of forest and nonforest with trees plots measured in the field by years from last measurement (constant disturbance rate for all cycl*

Cycle	Year	Total number of plots	Number of years since last measurement																					
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
10	1996	390	4	4	4	4		71													303			
11	1997	390		4	4	4	4		71													303		
12	1998	390			4	4	4	4		105													269	
13	1999	390				4	4	4	4		349													269
14	2000	390	4	4	4	4	8	7	7	9		343												
15	2001	390		4	4	4	4	8	7	7	9		343											
16	2002	390			4	4	4	4	8	7	7	9		343										
17	2003	390				4	4	4	4	8	7	7	9		343									
18	2004	390	4	4	4	4	7	8	8	8	8	7	8	9		311								
19	2005	390		4	4	4	4	7	8	8	8	8	7	8	9		311							
20	2006	390			4	4	4	4	7	8	8	8	8	7	8	9		311						
21	2007	390				4	4	4	4	7	8	8	8	8	7	8	9		311					
22	2008	390	4	4	4	4	7	8	8	8	8	8	8	8	8	7	8	63		225				
23	2009	390		4	4	4	4	7	8	8	8	8	8	8	8	8	7	21	268		7			
24	2010	390			4	4	4	4	7	8	8	8	8	8	8	8	8	35	251	9		7		
25	2011	390				4	4	4	4	7	8	8	8	8	8	8	8	47	241	8	9		7	
26	2012	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
27	2013	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
28	2014	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
29	2015	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
30	2016	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
31	2017	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
32	2018	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
33	2019	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
34	2020	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
35	2021	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
36	2022	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
37	2023	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
38	2024	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
39	2025	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
40	2026	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
41	2027	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
42	2028	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
43	2029	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
44	2030	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
45	2031	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
46	2032	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
47	2033	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
48	2034	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
49	2035	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
50	2036	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
51	2037	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
52	2038	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
53	2039	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
54	2040	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
55	2041	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
56	2042	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
57	2043	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
58	2044	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
59	2045	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
60	2046	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
61	2047	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
62	2048	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
63	2049	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
64	2050	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
65	2051	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
66	2052	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
67	2053	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
68	2054	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
69	2055	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		

Table 4.—*Total number of forest and nonforest with trees plots measured in the field by years from last measurement (higher disturbance than in table 3)*

Cycle	Year	Total number of plots	Number of years since last measurement																									
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
10	1996	390	4	4	4	4		178													196							
11	1997	390		4	4	4	4		178													196						
12	1998	390			4	4	4	4		178													196					
13	1999	390				4	4	4	4		178													196				
14	2000	390	4	4	4	4	19	18	18	23		207													89			
15	2001	390		4	4	4	4	19	18	18	23		287													9		
16	2002	390			4	4	4	4	19	18	18	23		287													9	
17	2003	390				4	4	4	4	19	18	18	23		287													9
18	2004	390	4	4	4	4	19	19	20	20	17	16	16	20		227												
19	2005	390		4	4	4	4	19	19	20	20	17	16	16	20		227											
20	2006	390			4	4	4	4	19	19	20	20	17	16	16	20		227										
21	2007	390				4	4	4	4	19	19	20	20	17	16	16	20		227									
22	2008	390	4	4	4	4	19	19	20	20	17	17	17	18	15	14	14	17		168								
23	2009	390		4	4	4	4	19	19	20	20	17	17	17	18	15	14	14	17		168							
24	2010	390			4	4	4	4	19	19	20	20	17	17	17	18	15	14	14	17		168						
25	2011	390				4	4	4	4	19	19	20	20	17	17	17	18	15	14	14	17		168					
26	2012	390	4	4	4	4	19	19	20	20	17	17	17	18	14	15	15	15	12	11	11	59		75				
27	2013	390		4	4	4	4	19	19	20	20	17	17	17	18	14	15	15	15	12	11	40	98		7			
28	2014	390			4	4	4	4	19	19	20	20	17	17	17	18	14	15	15	15	12	43	93	13		7		
29	2015	390				4	4	4	4	19	19	20	20	17	17	17	18	14	15	15	15	43	94	11	13		7	
30	2016	390	4	4	4	4	19	19	20	20	17	17	17	18	14	15	15	15	12	12	12	55	79					
31	2017	390		4	4	4	4	19	19	20	20	17	17	17	18	14	15	15	15	12	12	53	85	7				
32	2018	390			4	4	4	4	7	19	19	20	20	17	17	17	18	15	15	15	12	48	90	12	7			
33	2019	390				4	4	4	4	19	19	20	20	17	17	17	18	14	15	15	15	38	99	12	12	7		
34	2020	390	4	4	4	4	19	19	20	20	17	17	17	18	14	15	15	15	12	12	12	55	79					
35	2021	390		4	4	4	4	19	19	20	20	17	17	17	18	14	15	15	15	12	12	53	85	7				
36	2022	390			4	4	4	4	19	19	20	20	17	17	17	18	14	15	15	15	12	48	90	12	7			
37	2023	390				4	4	4	4	19	19	20	20	17	17	17	18	14	15	15	15	38	99	12	12	7		
38	2024	390	4	4	4	4	19	19	20	20	17	17	17	18	14	15	15	15	12	12	12	55	79					

Table 5.—*Total number of forest and nonforest with trees plots measured in the field by years from last measurement (high disturbance rate in 2000 and 20*

Cycle	Year	Total number of plots	Number of years since last measurement																					
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
10	1996	390	4	4	4	4		71													303			
11	1997	390		4	4	4	4		71													303		
12	1998	390			4	4	4	4		105													269	
13	1999	390				4	4	4	4		349													269
14	2000	390	4	4	4	4	19	18	18	23		296												
15	2001	390		4	4	4	4	19	18	18	23		296											
16	2002	390			4	4	4	4	19	18	18	23		296										
17	2003	390				4	4	4	4	19	18	18	23		296									
18	2004	390	4	4	4	4	19	19	20	20	17	16	16	20		227								
19	2005	390		4	4	4	4	19	19	20	20	17	16	16	20		227							
20	2006	390			4	4	4	4	19	19	20	20	17	16	16	20		227						
21	2007	390				4	4	4	4	19	19	20	20	17	16	16	20		227					
22	2008	390	4	4	4	4	7	8	8	8	7	7	7	7	6	5	5	7		292				
23	2009	390		4	4	4	4	7	8	8	8	7	7	7	7	6	5	5	7		292			
24	2010	390			4	4	4	4	7	8	8	8	7	7	7	7	6	5	5	133		166		
25	2011	390				4	4	4	4	7	8	8	8	7	7	7	7	6	5	177	105		22	
26	2012	390	4	4	4	4	7	8	8	8	8	8	8	8	7	7	7	7	94	176	14			
27	2013	390		4	4	4	4	7	8	8	8	8	8	8	8	7	7	7	174	111	5			
28	2014	390			4	4	4	4	7	8	8	8	8	8	8	8	7	7	209	76	6	5		
29	2015	390				4	4	4	4	7	8	8	8	8	8	8	8	7	241	44	7	6	5	
30	2016	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	225	7				
31	2017	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
32	2018	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
33	2019	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
34	2020	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
35	2021	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
36	2022	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
37	2023	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
38	2024	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
39	2025	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
40	2026	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
41	2027	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
42	2028	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
43	2029	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
44	2030	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
45	2031	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
46	2032	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
47	2033	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
48	2034	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
49	2035	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
50	2036	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
51	2037	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
52	2038	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
53	2039	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
54	2040	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
55	2041	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
56	2042	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
57	2043	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
58	2044	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
59	2045	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
60	2046	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
61	2047	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
62	2048	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
63	2049	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
64	2050	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
65	2051	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		
66	2052	390	4	4	4	4	7	8	8	8	8	8	8	8	8	8	8	55	232					
67	2053	390		4	4	4	4	7	8	8	8	8	8	8	8	8	8	51	237	7				
68	2054	390			4	4	4	4	7	8	8	8	8	8	8	8	8	45	243	8	7			
69	2055	390				4	4	4	4	7	8	8	8	8	8	8	8	37	251	8	8	7		

selection criteria and assumptions, but this time with a somewhat higher assumed disturbance rate. The disturbance rate still remains constant over time. The effect that a change in the disturbance rate has on the plots selected weather and other short-term effects. Plans are to incorporate these plots into AFIS to improve the model and increase the accuracy of the estimates. This merging of AFIS and FHM is facilitated by a decision made in 1995 to use the same field plot design for FIA and FHM.

This was what was planned prior to the Farm Bill of 1998.

> This bill mandates that each year a certain percentage of plots will be measured in each state. Given this we see the following as an opportunity of building on the current mandate:

This alternative approach contains elements of both the AFIS plot selection that was just presented and the plot selection mandated by the 1998 Farm Bill and previously advocated by SAFIS where 1/nth of the plots are measured each year regardless of disturbance.

Based on our experience with sample selection in the Aspen/Birch Unit, we propose the following sample selection strategy assuming a total sample of n plots each year:

1. Select the FHM plots for remeasurement every 4 years say n_1 each year. This yields a sample of about 5 percent of the plots, 25 percent of which would be measured in each of the 4 years, which yield reliable growth and mortality measurements (measurements of less than 4 years may have too much measurement error in them to be useful).

2. Implement a grid subsample of x percent of plots each year, n_2 plots, so that all plots would be measured over 100/x years. Typically x might be 5 percent so that all plots would be measured in 20 years.

3. Select a certain number of plots (n_3) in the disturbed and a smaller percentage of plots, say n_4 actual plots, in the undisturbed strata.

4. Allow for a certain number of additional plots that can be remeasured in response to specific needs in any given year, say n_5 plots.

The above is an idealized version of plot selection, resulting in $n_1+n_2+n_3+n_4+n_5$ plots. If this number exceeds n, we would have to cut down on n_3 and/or n_4 to ensure that actual number of plots equals n.

ESTIMATION ISSUES

Although we like the concept of giving all sample units equal probability of selection each year, as we are instructed to do under the 1998 Farm Bill, we believe this may be unrealistic particularly as states, industry, and other users see opportunities of getting more frequent inventory information for the state and parts of the state. If unequal sampling probabilities are used, estimation becomes more complex and users of the data must be more aware of the complexities of sampling design in their analysis of the data.

Estimating parameters such as totals is not difficult as long as the probabilities of selection for the sample plots are kept track of properly. Difficulties are anticipated in the joint probabilities of selection for units that are needed in classical variance estimation. If it is difficult to obtain such joint probabilities of selection, we plan to use bootstrap techniques for variance and confidence interval estimation (Schreuder *et al.* 1993). Even if such joint probabilities can be readily computed, we will probably use bootstrapping since such nonparametric techniques generally yield more reliable confidence intervals for estimates.

It may be possible to maintain a base equal probability sample and use the proposed sampling strategy for intensification purposes only. There are advantages and disadvantages to such an approach. The base sample could serve users who wish to avoid the complexity of the intensified sample. This sample would provide consistent, unbiased estimates of population parameters based on simple, widely used methodology. Users of the base plus intensified samples would need to understand the complexities of the intensified sample and incorporate them into their estimation procedures. By doing so, they could obtain better estimates of many parameters. The possibility of conflicting estimates from the two approaches is a real problem and is one that would require a great deal of education for those using FIA data. The higher cost due to more frequent remeasurement of the simple, equal probability approach will have to be compared to the complexities and possible apparent inconsistencies of the unequal probability approach.

LITERATURE CITED

AFIS. 1992. Annual forest inventory system. Problem Analysis. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Inventory and Analysis Program. Unpublished document. 51 p.

Hansen, M.H. 1990. A comprehensive sampling system for forest inventory based on and individual tree growth model. St. Paul, MN: University of Minnesota. 256 p. Ph.D. ids.

Jakes, P.J. 1980. The fourth Minnesota forest inventory: area. Resour. Bull. NC-54. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 37 p.

Kingsley, N.P. 1992. Forest statistics for Minnesota's Aspen-Birch Unit. Resour. Bull. NC-128. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 42 p.

McRoberts, R.E. 2000. Sources of uncertainty in annual forest inventory estimates. In: Hansen, M.; Burk, T., eds. Proceedings, Integrated tools for natural resources inventories in the 21st century; 1998 August 16-20; Boise, ID. Gen. Tech. Rep. NC-212. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 207-213.

Schreuder, H.T.; Wardle, T.D. 2000. An annualized forest inventory for Nebraska. In: In: Hansen, M.; Burk, T., eds. Proceedings, Integrated tools for natural resources inventories in the 21st century; 1998 August 16-20; Boise, ID. Gen. Tech. Rep. NC-212. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 171-175.

Schreuder, H.T.; Gregoire, T.G.; Wood, G.B. 1993. Sampling methods for multiresource forest inventory. New York, NY: J.Wiley and Sons. 446 p.

Smith, W.B. 1983. Adjusting the STEMS regional forest growth model to improve local predictions. Res. Note NC-297. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 5 p.

Spencer, J.S., Jr.; Ostrom, A.J. 1979 Timber resources of Minnesota's Aspen-Birch Unit, 1977. Resour. Bull. NC-43. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 52 p.

Williams, M.S.; Schreuder, H.T. 1993. A comparison of algorithms for selecting an optimum sample from H strata using k variables. In: Proceedings Conference Applied Statistics In Agriculture. Manhatten KS: Kansas State University: 209-219.

Some Practical Aspects of Designing a Large Inventory

Dr. Kim Iles

Abstract.–Designing a large multiresource inventory is horribly difficult. It is not work for faint hearts, and the 250,000,000-acre size of British Columbia is not a trivial problem. Completion of the details (as opposed to stopping the work) is a process prone to collapse. After that point, implementation is also likely to fail.

There have been some changes in the world, and perhaps it is time to abandon some concepts like stratification, random sampling, class averages, fixed plots, and many other notions that never were very good ideas, and where far better alternatives have long been available. The problem is tradition and myth on the part of forest inventory people, and a lack of experience on the part of some specialties.

The idea of a large-scale inventory might be clear to foresters, but it is *not* intuitive to other disciplines, in particular the ecological side of the business. In an era of coordinated inventories, this complicates matters. To complete the grinding number of details, there is a special need for practical people who at the same time can conceive of the principles and handle change. Hard-nosed, flexible, experienced, imaginative, diligent workers might be plentiful where you come from, but we had to work hard to conserve ours. If you confuse "specialists" with "experts" then the chances are that the project will die young. Real problems get far too much *input* and far too little *output* in any organization that harbors some vague notion about a democracy of intellect.

There is a critical need to get the political creatures away from the technical side of the business and let them serve their own purpose. Too little attention to details will sink the ship (and these details are grindingly difficult). However, heading the ship in the wrong direction is by far the most serious error, and it requires tedious repetition to keep the principles in the forefront. Details are necessary; principles are important. Don't confuse the two concepts.

The BC inventory has made good use of some non-traditional approaches. None of these are entirely new, but the combination and thinking is not the common approach to these problems. The use of the Internet both to distribute and to document issues has a powerful potential. In the final analysis, the social element is critical for both design and implementation.

Two weeks before Christmas of the year 1600, some 350 men were killed because of a fool who wanted to be in charge. Antonio de Morga was the lieutenant governor of the Philippines, and the pirate sails that passed by his colony gave him the opportunity to make his mark. He had ordered his largest ship, the "San Diego," beefed up for an encounter, with extra guns on the top decks and other quick changes that might enhance his opportunity for fame. The "little people," the mere craftsmen who understood these matters, tried to dissuade him. They probably explained about "the center of gravity" vs "the center of buoyancy" and other non-managerial issues, but were put in their place quickly (for de Morga was, after all, "in charge"). The ship was launched, as ordered. Within a few hours, it sank due to overloading. De Morga, along with many of the rats who so often occupy the upper decks in life, made his way ashore and immediately wrote to Spain to give his stirring account of the battle (before they heard otherwise). You *know*, of course, what happened. He was promoted. He was rewarded. He was judged a great success (the alternative is simply too embarrassing to consider). He was given a larger command.

Biometrician, Kim Iles & Associates Ltd., 412 Valley
Place, Nanaimo, BC, Canada V9R 6A6
e-mail: kiles@island.net.

National Geographic reported the raising of the ship in the 1990's because it was a treasure, historically. The magazine staff were able to find secret testimony, and there among the accounts of the surviving crew were the words of Lt. Almayda, who recorded the judgment of history upon this "Bozo the Clown" as follows:

> *The loss "was all due to the bad leadership and lack of experience of Dr. de Morga, for trying to be in charge of something he knew nothing about."*

Now we all know this guy, don't we?? We have all worked for these people. They are like the characters of the TV series "Highlander" who never die off. They drift through the ages causing trouble and grief. They are always there, as constant as dump rats, ready to sink the ship. They are drawn to inventory projects like flies. You will have to kill them off somehow.

WHAT WAS THE TASK?

Our inventory was for about 100,000,000 ha. That's a quarter of a *billion* acres. It's larger than the entire USDA Forest Service land base. It was to be one of those integrated, multiresource, "we are all in this together" composites of many needs and specialties. In other words, a "modern" inventory. The potential for disaster was enormous.

However, we seem to have pulled it off (the design, that is—the *execution* is still very much up in the air). Since many of you are in this racket, some of the lessons might be of interest, and perhaps of use. It was a big opportunity to take a single-agency dominated inventory process on a large land base and modernize it. One of our tasks was to develop processes for many kinds of measurements that could be introduced throughout the province. We needed practical improvements to methods that had drifted off track, fallen behind, or were wrong-headed from the outset. There were many of these. Some had been etched in stone by the provincial government, and many of them had seeped deeply into the bones of technical folks at all levels.

Now you do not have to be very bright to know that this is a bad-news situation. The probability of failure was high, and the work was going to be difficult. At that time I was not connected to the ministry, but the director wanted me to be involved with the design and with organizing the committee. I was impressed that he always seemed to approach me in a bar. "Would you like to do this project, Kim?" No. "You will enjoy it." *No.* "How about if we do it this way?" No!! On the third or fourth approach, he simply said, "What do you want? You tell *me* what you want and how we can do this." Now this struck me as unusual. *This* kind of director might actually be able to pull this off (and he did). I signed on, and did the work as an independent consultant (which I still am).

I was appointed as the inventory design specialist, working with a committee of folks who would know about a variety of technical requirements and problems. I had some influence over many of the principles we adopted. Some of the main ones were:

1. **The entire land base would be covered, by a valid sample.**
   [Sample points were chosen systematically from a sorted list.]
   [Thus far, we have given each land type equal weight.]

2. **We would use older techniques, with a track record—nothing tricky.**
   [Any methods begging for complications or loss of credibility we dropped quickly.]

3. **We would obtain estimates, and correct those with ground sampling.**
   [Estimates could come from anywhere, but using photos as a default.]

4. **We would assume a hostile review by intelligent opponents.**
   [Therefore, we planned audits and other credibility enhancing processes.]

5. **Processes would be designed for wide, thorough, and critical review.**
   [Designed, therefore, for display on the Internet and word processor files (delivered by Internet) that could be word-searched and compared to other sections.]

6. **The details would be worked out ahead of time and tested.**

7. **We used actual craftsmen who knew the business.**
   ["Experts," not "specialists." An expert really *knows* a field; a specialist just has a narrowly defined job. Anybody with a title can be a specialist. Anyone who does not know the difference ... is a specialist.]
   [Having a Ph.D. was not a fatal flaw, but it was a really bad sign.]
   [The members were largely non-ministry people.]

8. **Nobody was appointed to "represent" anything. They were there to work.**
   [People were surprisingly willing to do this.]
   [People were to be included "because of their deeds, not their needs."]

9) **We *would* measure old growth, biodiversity, and a few other difficult things.**
[This meant stepping on the toes of those who *would not* do so.]

Now this was not going to be easy. It was too big a job without the help of your friends. In BC, we are fortunate to have a number of people who have made forest inventory their life, and they have a wealth of knowledge, experience, and judgment to offer. We asked them, and they participated. It made all the difference. The problem was always to allow them to succeed against a chorus of de Morga's.

The committee produced two reports. The initial report said: "Here is the situation, here were the past mistakes, here is a useful view of it." The final report said: "Do it with these principles and approaches." Every committee member agreed to every sentence in every paragraph. They were encouraged to write dissenting opinions (to be published with the report) if they wished. None chose to do so. We did not get into details, simply because we were not the most competent people to do so. "Working groups" were formed of people who could do the details, with committee members present who could explain the guiding principles and adjust the overall goals when appropriate. All this took several years.

OVERALL DESIGN

We had two basic problems: how much is there, and where is it. In the first phase of the inventory, we make an estimate for several variables for every polygon in British Columbia. Remember that we are talking about a huge area. In some cases we will use past inventory estimates; in some cases new photointerpretation will be done. This would put the results where they belonged, and could help with the total estimate.

The ground data would establish the total, in some cases by stratified sample averages, in some cases by correcting previous estimations by regression or some similar technique.

For Trees: five variable plots. One measured, four "count plots."
For Ecological Information: A (too large) fixed plot for a species list, percent cover and ecological label
A soil pit
Range transects for brush cover
Coarse Woody Debris transects

Many details are available on the Internet, currently at:
http://www.for.gov.bc.ca/RIC/PUBS/TEVEG/gsp/contents.htm
http://www.for.gov.bc.ca/resinv/Veginv/home.htm

The province is broken into about 40 inventory units. Each will be done independently. About 200 sample positions are chosen with a systematic sample from a sorted list. The probabilities are virtually equal, at least within an inventory unit. Each sample point has a weight assigned to it (essentially the amount of area it represents; usually they are very similar). These are lightly monumented so that tree growth and other changes can be measured 5 or 10 years from now. On the central plot, the distance to each "in" tree is recorded for later growth monitoring. The final 15 m to the sample point is carefully measured so that the field crew does not make subtle shifts in the exact position. It will be interesting to see how often we land inside trees or streams. For plots near the polygon boundary, a semicircular plot is used. There are about 16 cards to be filled out on each plot. The plots are taking too long, and we need to devise ways to reduce that field effort.

The total volume in each species (as an example) is distributed back over the land base using the estimates for each polygon. By fixing the total, we can maintain unbiasedness even if we decide to re-estimate part of the inventory, or further adjust polygons in the future. This will allow us to incorporate a variety of biased and non-sampling data from other sources. There are a number of audit, check cruising, and tree dissection procedures to check for measurement bias and to aid credibility. The precision of polygon accuracy is determined by a separate process.

WHAT DID WE DO RIGHT?

1. **We got the principles right the first time.**
   We emphasized the principles, *and kept doing it*, even during grinding detail sessions — it saved us from making many technical mistakes.

2. **We met regularly, with a fairly stable and highly technical group.**
   Social time was critical here. The perfect meeting would include lots of time to eat together, visit the bar, and become a family. If you want people to fight out technical issues, with no quarter given, then they have to like each other.

3. **We used the opportunity to train lots of people, and introduce a common view to various parts of the province.** Even if the inventory is never implemented, we will never shrink back to the same size.

4. **We used first rate and experienced people whenever possible.**

   You can have whomever you want attend the meetings, but the voting and working core has to be competent—not there for training. The marginal people had a rough ride. The political animals thought we were mad. The good people had fun. The work was first rate, and you cannot do that with amateurs (although you can pretend to). You had better have a bone-deep appreciation of the importance and contribution of these people.

5. **The work was done by the committee, not farmed out to contractors.** (Unless it was very mechanical, of course).

   Nobody defends a poor idea when they are personally suffering to develop it. People who are pretenders drop out very early in the process if you change the question from "What do you want?" to "What do you want *to contribute*?" The emphasis in our committees was not on "input"; *it was on output.*

6. **We did not commit to a starting date early in the process.**

   This would have rushed some decisions, and the work would have suffered.

7. **Training and educational concerns were part of the process.**

8. **The processes were put into compartments that could succeed or fail without dragging the rest of the inventory down with them.**

   This took the heat off some of the groups, who could develop the process at their own rate and join the parade later (or just watch). Closely linking the various parts of the data gathering would have been a mistake. This was good psychology as well as good management.

9. **Individuals (or very small groups) did the work. The committee reviewed it.**

   This is a big contrast to groups that sit around and wonder what to do together. That person was expected to lay out the leading ideas and suggest one they could defend. If they could not decide, they were not doing their job. If someone could not perform, they were hosed off forthwith and given no further work of that type. If the work was sloppy, they were given a rough ride and usually performed the next time. The time of experienced people is too valuable to waste. Chit-chat time was for the social hours. Theoretical issues need to be just as explicitly examined and understood as any list of codes.

WHAT DID WE DO WRONG?

First, let me be clear. Every one of these problems was a "people problem." There were NO serious technical problems. The errors resulted because we weakened in applying the principles just listed. When we lost our nerve and tried to accommodate some form of insecurity or incompetence from someone—things always went wrong. Some of them went *badly* wrong, and we are still working to correct them. In most cases, the error was made in the face of clear advice that it would be a mistake.

1. **A few people were given work based on their needs, not their competence.**

   This was always a mistake. At the very least, it delayed and annoyed valuable people.

2. **Compromises were almost always bad.** It is better to clearly win or lose.

   New or better ideas were always welcome. In some cases we had to decide between two work able ideas. It is better to make a mistake than to create a compromise. I believe that this is so because of issues involving balance and detail. Often, these matters require a clear, complete view of the issues. A compromise muddies the water for both parties, and when something goes wrong it is always harder to fix than if a pure strategy had been adopted. There are too many loose ends in a compromise.

3. **Computer people were allowed to take over work at which they were incompetent.**

   This is always a mistake. In our case it has been an expensive one. Keep their tiny little hands off data and database designs they do not understand (and I say this having personally worked as a computer programmer and systems analyst).

4. **We did not have a permanent field crew to continuously try out ideas.** This caused delay.

   This would have saved a great deal of elapsed time and trained critical staff. I would recommend that such a crew be established in every similar project, and that they attend every meeting to know the background and intent of the designers.

5. **A few people who were not technically qualified caused a lot of expense and delay.**

   In our case, I would estimate about 1-1/2 years of delay. The only antidote seemed to be to make them do the work and to refuse to listen to any idea they had not personally tested in the field at least 20 to 40 times. This kills a lot of dumb ideas without too much delay.

6. **We did not communicate well enough to groups outside the committee.** Everyone wanted to be involved with this, but it never got done.

7. **The review of well thought out processes by marginally involved or uninformed people was a negative influence.**

8. **The decision to use contractors to do this work, rather than a permanent staff, has been a missed opportunity.**

These mistakes were made even with a director who was capable of direct and timely action. Good people have plenty of opportunity to do other things, so this kind of project is not the place for a lack of leadership or an inability to handle conflict.

IF YOU WANT TO DESIGN A COORDINATED MULTIRESOURCE INVENTORY—EXPECT TROUBLE

My advice — **from a technical perspective**

1. **Keep processes separate so you can disconnect them (or subsample) when some fail.**

2. **Make it so that people can put more work in themselves to improve particular answers.**
   If the "Friends of the Upland Squirrel" want to put in an extra 2,000 plots, give them a sampling plan for doing it and turn them loose. If they want to use your data, provide it. If they want to sample their own way and combine it with your results, *lock the door* and refuse to talk to them. If they will not use an actual sample or compatible estimates (check it, by the way), then tell them their data will help decide the *distribution* of upland squirrel habitat, *not* the total amount. If there is more habitat in one watershed, there will have to be less habitat in the others.

3. **Work on the methods, not on budget or control issues**. The methods are hard enough.

4. **Stress compatibility and combinability, not coordination of effort**.
   Make everyone think about doing it themselves, alone, with the possibility of combining it later. Make it a collection of many separate working parts, not a huge machine that is welded together. Get cooperation by producing an excellent system, not by coercion.

5. **Definitions without a sampling method are bad business**.
   If possible, make the sampling method part of the definition. The work is harder, but more likely to succeed.

6. **Define a common sample point, and have everyone sample it any way they want**.
   Concentrate on describing a point, and let them incorporate the area around that point any way they choose. I have no faith that a common plot will ever work. In our system, everyone describes the same point by different size plots, transects, etc.

7. **Keep your data in hard copy. Fight the urge to round or classify. Assume you will recalculate.**

8. **Expect to recompile the data and to accommodate new definitions (by subsampling).**

9. **Decide for yourself how to measure old growth, biodiversity, and other difficult issues.**
   Lots of people will want to tell you how to do this by methods they would never use themselves. In some cases they will simply enjoy the process of obstruction. Ignore them and get the job done. Think about providing information they can subsample and data that will help decide differences of option. With luck, they will only have to revisit 10 percent of the ground locations to apply their own (eventual) definition.

10. **For biodiversity, stick to plants on a fixed plot small enough be practical in the field.**
    Keep the plot size constant.

11. **Ignore setting sample size and selecting which of several estimation procedures to use for as long as possible.**
    We waited until the process was finished. A system that can be scaled to work with any size land base is more likely to be general, flexible, and useful to many other people.

12. **Work on the basis of providing a method without a commitment to ever do that work**.
    This keeps the budget issues at bay while you do the technical work. In many cases, the overly expensive systems can be dropped or subsampled after the details are worked out.

WHAT ARE THE SOURCES OF THE PROBLEMS ?

Ecosystem People are a Problem

You must understand, these are people who do not use data a great deal and use sampling very little. There are exceptions, but they are rare. They do case studies, and give "typical areas" *names* rather than numerical values. Because they often move plots into "typical areas," their systems have a tendency to be incomplete. There may be no ecological code for roads because they do not occur when "typical areas" are chosen.

This is not a criticism. Foresters have needed almost 100 years to learn to sample trees that are long-lived, self-recording, easily seen, and do not move. Imagine measuring critters that breed quickly, move, die, migrate, hide, bite, and are nocturnal into the bargain. Their work is difficult, and the problems are difficult enough that ecologists have not been as deeply into the process as we have been. Little wonder that they are not familiar with many of the concepts.

The most serious problem is that they often do not understand the concept of an inventory process, where the answer is a combination of many observations, each of which is individually "inadequate." They want a *complete* description of each sample point. The concept of partial information at each point is hard for them to understand. No forester would expect to get every tree species in a polygon with one or two plots, but an ecologist will attempt to do that by putting in a very large plot or moving the plot to a "typical" place.

I have mentioned the problem of incomplete systems, but there is also the problem of vague definitions for which there is simply no way to sample. Suppose that "Old Growth" requires 10 snags per hectare and I put in a 1/10 ha plot. It contains no snags. Can that sample point be in an old growth area? Answers to these questions become a serious roadblock to the details of designing an inventory. We have something to teach this group, and something to learn as well. If there is a future for forest measurements, it is in measuring all kinds of things, not just trees. We need to get involved with these problems and figure out how to solve them.

There is a serious need to test ecological measurement methods before they are seriously considered. There are often problems with these approaches, and many of the suggestions were entirely untested when they were proposed. A useful rule is 20 to 40 repetitions done *personally* by whoever is suggesting the method. Otherwise, do not consider it. Whenever we did so, it was a mistake.

Foresters are a Problem

Foresters have a tendency to round, interpret data into classes, and ignore parts of the land base. They have a deep conviction that past practices have virtues that even a brief examination would dispel. They have a bone-deep inclination to stratify even when it makes no sense at all, followed by a need to have plenty of samples in each of the strata. At the same time, they forget to attach weights to samples in case they are used for other purposes and instinctively feel that taking data in the middle of a stand just has to be a good idea. They worry about sample size too much, and sample placement too little. For some reason they have a deep faith in the power of "consistency," which allows them to do the most bizarre sorts of measurements in the sure and certain knowledge that it is OK "as long as the process is consistent." Removing these ideas is a painful and bloody process for everyone.

Local Heroes, Academics, and Reviewers are a Problem

Reviewing the process is a really important function. Done well, it can improve the balance, and particularly the credibility, of the inventory plan. Done poorly, it just raises anxiety and provides a place for outsiders to quibble about what the design team has done. The key is to get people whose judgment is well respected and allow them to get a *good* look at the reasoning and details of the process. The mixture of technical expertise and experience is critical.

First of all, publishing papers is not the same as experience. This escapes many people. On rare occasions there is a specific question that you really need a narrow specialist to solve, and on rare occasions they can be brought in to do that. More often, they want *you* to change the question or the process so that they can point to a page in Cochran and say "there it lies!" In our case, one reviewer suggested that we put in random samples so that the variance estimator was exact and simple. The effect of this suggestion was not considered by the reviewer. It is hard to tell how much will eventually have to be done to kill this foolish idea. These people need to spend several weeks with the field crew. At that point you will no longer get poor advice from them. This, however, is not the fault of the reviewer. It is the fault of a system that will ask a graduate student with no experience in the field to review a process they have no way to understand.

Choose a few very solid people in the specialties that are critical and keep them lightly involved throughout the process. These folks should be heavy on actual experience and the kind of balance and judgment that comes only from that source. They need to know the people involved and the history of the project. This will solve 90 percent of their problems and concerns. As an additional step, an outside and rather formal review of the process at the end might be very useful.

MANAGING THE PROCESS: WHAT TO EXPECT

Designing a multiresource inventory will take some time. The people involved cannot do it on their lunch breaks. The group that does this will have to be fairly permanent, technically competent, and socially comfortable. I do not believe that you can get to that stage quickly. Until it happens, however, progress will be slow. Use this time to organize the paper trails and establish some administrative rules. Make some friends at all stages, if possible.

Stage 1

First, the manager-politicos will arrive. This cannot usually be avoided. They want to make sure that their interests are looked after. See that this happens. Make sure that the approaches and principles of interest to them are laid out so they will leave as soon as possible. They have their place, but it is not on an inventory design committee. When any serious time and effort are required, they will be inclined to move on. Leave open the idea of a steering committee that they can attend, but make sure that the working people are insulated from that committee.

Stage 2

Next, the handmaidens of the managers will arrive. They will be chosen because their managers consider them politically reliable and know that they will report any devious behavior. They will also usually be able to spot real ability in your group, even if they do not trust it. They will get a fair idea of the technical goals, but when the work builds up they will want out. They, in turn, will eventually send their technically competent people when they are convinced that you are actually working on the problem rather than maneuvering in some way that needs watching.

Stage 3

Once the craftsmen arrive, you can start making real progress. This is the time for working out the principles in detail, training eventual staff through their attendance (not membership), and field testing. At the stage that all the major issues are resolved and the technical issues are clear I would predict that you are 20 percent done. By the time that a procedures manual is written and field forms are tested, I believe that you will be about 60 percent finished. When one or two pilot projects are successful (failures do not count), you have another 10 percent to do, but that will be a tolerable workload. Do not firm up databases, edit processes, or handheld applications until the whole process works well on paper.

Now it is possible that you might move directly to the third stage, *but I think that it is unlikely*. This is all serving a purpose, and some tolerance to the process should be shown. This kind of tail-sniffing takes time, and trying to shortcut the process might well backfire. Once the craftsmen are assembled, it is important to keep that critical mass of competence. The same people that are of great help in doing this work are also sources of many of the really precious commodities needed by a forest inventory—support, tolerance, patience, credibility, and goodwill. Someone needs to insulate this technical group from the mechanical irritations and the bureaucratic problems. At the end of each stage, make sure that appropriate credit is given. You will need these people again.

If you can make this process work, it's a wonderful experience. I'm glad I did it. I learned things that I would not have otherwise believed. The committees that functioned were proud of their work, had fun, and contributed something really useful. The failures had very little fun, although they did all the politically correct things about running their committee. They did not make a contribution. *It is their own fault—for trying to be in charge of something they knew nothing about.*

If you cannot get it right, then you might want to stay on the dock and let this ship sail without you. You have that choice these days, although Lieutenant Almayda did not. The de Morga's will run the ship at some point. Make sure they don't organize it if YOU are going to be on board.

ACKNOWLEDGMENT

I would like to thank the reviewers: Dr. Dave Marshall, Forest Science Department, Oregon State University, Corvallis, OR, USA, and Dr. Don Reimer, D.R. Systems, Nanaimo, BC, Canada.

Forest Resource Inventory Assessment in Gunung Rara Forest Reserve, Sabah, Using Stratified Field Sampling

Kamaruzaman Jusoff

Abstract.—The objective of this paper is to assess the current timber volume by stratified sampling on a proposed plantation area. The study area is located in Gunung Rara Forest Reserve in the district of Tawau, Sabah, Malaysia. The size of the study area is 106,310 ha and consists mostly of logged-over forest lying in low areas (<240 m above sea level) with a slope of less than 15 degrees. However, a third of the area lies between 240 and 600 m above sea level and consists of rolling hills with slopes of 15 tp 25 degrees. The survey was conducted by a limited field sampling undertaken in June 1997. Trees within 25 m on either side of a line were measured, plotted, and established in each of the five main forest stand types to obtain data for estimating timber stocking by species group and size classes. The position, species group, diameter classes, and crown width of all trees with diameters greater than 20 cm were recordeded. A total of 13.75 ha of sample plots was established, representing about 0.01 percent of total study area. Trees were enumerated according to three broad species groups—Dipterocarps, non-Dipterocarp, and pioneer species—on one-tenth ha subsample plots (20 m along sample line by 25 m each side of sample line). Cross-comparisons were undertaken of the forest stand type areas and timber volumes from previous assessment. Data were then compiled for each of the 10 annual plantation working blocks. For each stand density, an average timber volume yield was estimated. The timber yield by species and diameter class was estimated based on the Stock Table Data from Sabah Forest Department Inventory 1995/96. The area proposed for plantation in each of the 10 annual working blocks was identified on the Forest Plan Map. Tables illustrating tree stocking by timber stand density class, tree stocking by species group, and tree stocking by tree size class were presented. An estimate of timber volume was calculated for each five diameter classes based on net recoverable tree volumes per tree. Based on a preliminary analysis and compilation of field data, the volumes of timber and pulpwood were about 120 and 40 m^3/ha, respectively, of standing volume of commercial timber trees (> 40 cm diameter at breast height) and small diameter pulpwood (<40 cm diameter at breast height). Future studies will correlate the present field sampling data with hyperspectral imaging and integrate them into geographical information system spectral signatures of the main five forest density classes.

Benta Wawasan Sdn.Bhd., a wholly owned subsidiary of Innoprise Corporation[1], plans to establish an industrial forest plantation on approximately 106,310 ha of Yayasan Sabah's Forest Concession area[2]. This project is an integral part of the Sabah Softwoods Sdn. Bhd. (SSSB)[3] industrial tree plantation development program, which consists of a 60,000-ha forest plantation area[4] (about half of which has been planted) plus the planned Benta Wawasan forest plantation area. The addition of the

---

Chairman/Associate Professor, Remote Sensing/GIS Research Group, Faculty of Forestry, Universiti Putra Malaysia, Serdang, 43400 Selangor, Malaysia.

[1] *The holding company that manages Yayasan Sabah's (Sabah Foundation) commercial operations, including: Pacific Hardwoods, Silam Forest Products, and Sabah Softwoods.*

[2] *Sabah Foundation, a statutory state corporation, was established in 1966 to use commercial forestry revenue for the social benefit of Sabah residents. It has a 100-year concession on approximately 1 million ha of forest. The Benta Wawasan plantation represents about 10 percent of the total Yayasan Sabah concession area.*

[3] *Sabah Softwoods Sdn Bhd (SSSB) was established in 1974, as a joint venture between Yayasan Sabah (60 percent) and North Borneo Timbers Bhd.(NTB) (40 percent).*

[4] *In two blocks adjacent to the southeast boundary of the Benta Wawasan Forest Plantation Area.*

Benta Wawasan plantation brings SSSB's total area targeted for industrial forest plantation development to 166,000 ha, making it Malaysia's largest commercial forest plantation.

Before the plantation program is implemented, there is a need to assess the growing stock and timber volume resources of the Benta Wawasan Concession area. The task of extensive forest inventory assessment reporting on tropical forest lands is not easy. The tropical forest is ecologically diverse, certain data are lacking, data types often are not well integrated, and past forest inventories do not allow for trend analysis (Kamaruzaman 1998). Kohl (1996) reported that a multiphase sampling design for tropical forests inventory has some major disadvantages that limit its application in forest surveys. In a study by De Gier and Sakouhi (1995) using a stratified random sampling procedure, a woody biomass inventory was successfully carried out in a forest area of Tunisia.

To address the need for information, a stratified field sampling design technique is used for estimating results for large forest areas and as ground truth data in airborne hyperspectral image processing for future extensive forest survey analysis. The overall objective of this forest inventory assessment is to review and verify previous estimates of the timber volumes on the proposed plantation area and to prepare a quantitative assessment of timber resources. The specific objective is to assist Benta Wawasan's management in forecasting annual timber yield from plantation forest harvesting.

METHODS AND MATERIALS

Data from the previous forest resource assessment were reviewed and verified (or revised) using the following procedures :

- Limited field sampling was undertaken in June 1997. Linear sample plots were established in each of the five main forest stand types to collect tree data for use in developing estimates of timber stocking species groups and size classes.
- Cross-comparisons were undertaken of the forest stand type areas and timber volumes from previous forest resources assessments, with those of the current forest inventory assessment , to verify or revise timber stand area and volume estimates for the Benta Wawasan plantation area.
- Data from these confirmed or revised estimates were compiled for each of the 10 annual plantation working blocks.

Location and Description of Study Area

The project area, which consists of 106,310 ha of mostly logged-over forest is located about 40 km northwest of Tawau in the Kalabakan and Gunung Rara Forest Reserves in the district of Tawau, Sabah (fig. 1).

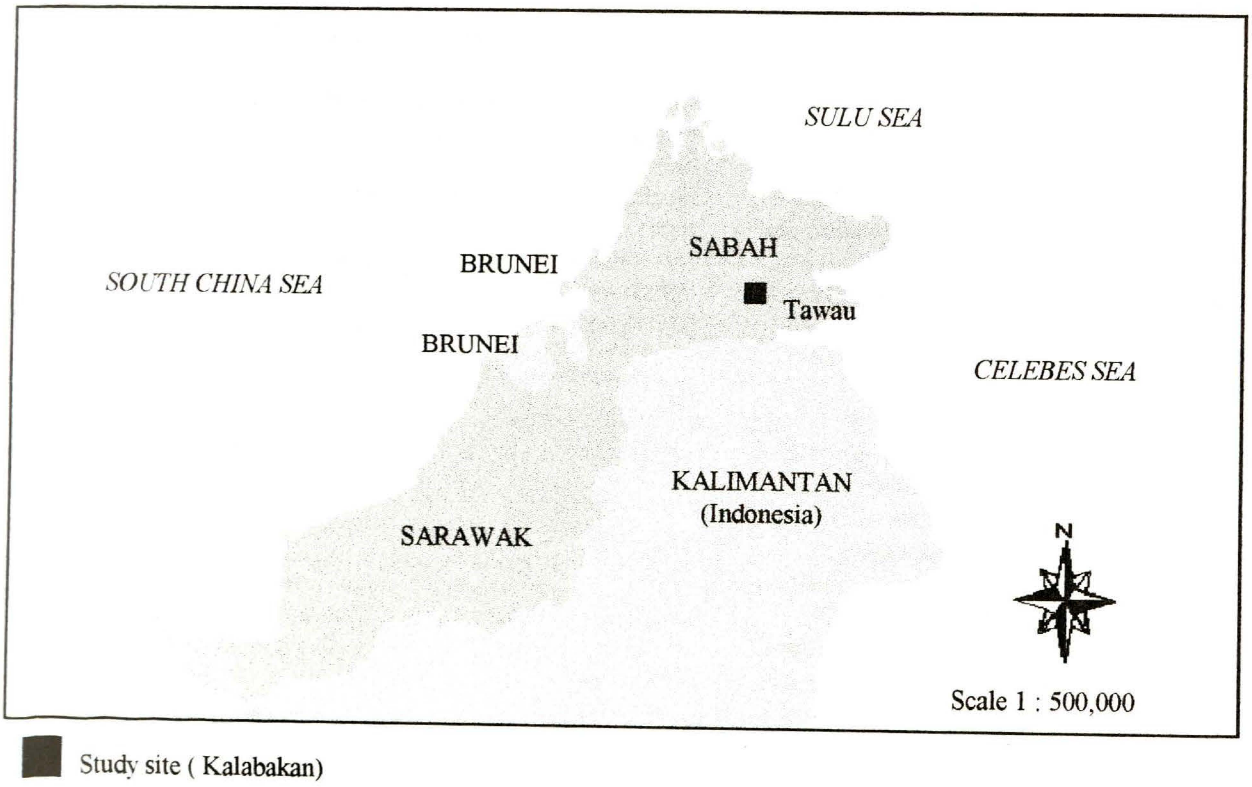


Figure 1.—*A map of Malaysia showing the location of the study site.*

Most of the project area (60 percent or 64,100 ha) consists of low elevation areas (<240 m above sea level) with relatively gentle topography (slope <15 degrees). A third of the project area (35,493 ha) lies between 240 m and 600 m above sea level and consists of rolling hills with slopes of 15 to 25 degrees. A relatively small portion of the project area (6 percent or 6,708 ha) lies at higher elevations, with generally hilly, broken topography and slope of >25 degrees.

The soils of the project area are predominantly mudstones, sandstones, and miscellaneous and igneous rocks of the Gumpal, Crocker, Malubok, Lokan., Kretam, and Bang Associations. These six soil types account for 88 percent of the soils in the project area. The geology of the eastern portion of the project area is dominated by chert-spilite-greywacke and limestone formation. In the west, the Tanjong Formation dominates with mudstone, siltstone, and sandstone materials.

The project area is divided into 10 annual working blocks that are further subdivided into 2,000- to 2,500-ha sub-blocks. This forest inventory assessment focuses on the quantification of forest resources on each of the 10 annual working blocks, as described in the following section.

Forest Inventory Data Sources

This forest inventory assessment is based on two previous forest resource assessments, supported by additional field sampling. The previous forest resource assessments include:

- Forest inventory of the Yayasan Sabah Concession conducted by Sabah Forest Department in 1995/96. This inventory included the Kalabakan, Gunung Rara Forest Reserve, which is part of the Benta Wawasan plantation area. This inventory involved extensive field sampling.
- Timber volume estimates from a detailed aerial survey of project area by C.H.Williams, Talhar, and Wong in 1996. No field samples were undertaken to confirm these estimates.

The 1995/96 Forest Inventory of the Yayasan Sabah Forest Concession included 430 "L" shaped inventory sample plots in the North Borneo Timbers (NBT) block, which is located within the Kalabakan/Gunung Rara Forest Reserve that encompasses the Benta Wawasan plantation area. A Stock Table for this block shows the timber volume per hectare by species group and tree size class. This Stock Table is used in estimating the species group and size classes of timber available from plantation land clearing on the Benta Wawasan plantation area.

Forest Area and Estimated Timber Yield

The project area was stratified into five timber stand (density) classes based on data from the previous forest resource assessments. For each stand density, an average timber volume yield was estimated as illustrated in table 1.

Table 1.—*Area and Timber Volume by Forest Density Class*

Stand density	Avg. timber yield	Area	Approx. total timber yield
	m³/ha	*ha*	*m³*
Very high	60	4,626	277,560
High	40	5,326	213,040
Medium	20	17,489	349,780
Low	10	23,763	237,630
Very low	5	55,106	275,530
Total area volume		106,310	1,353,540

Data source: 10-year working plan of Benta Wawasan plantation area.

Because most of the forest area has been logged, the average timber yield is relatively low (12.73 m^3 per ha). According to these estimates, the commercial timber volume on each proposed plantation working block is 1.35 m^3.

Species and Size Distribution of Timber Yield

The timber yield by species and diameter class was estimated based on the Stock Table data from the 1995/96 Sabah Forest Department Forest Inventory of the NBT block. The data are summarized in tables 2 and 3. The total volume of all trees greater than 20 cm diameter at breast height is 135 m^3—66 percent in trees of commercial timber species and 50 percent in commercial trees with diameters greater than 40 m^3.

Table 2.—*Average timber volume (m^3/ha) by species group and diameter class.*

Species	Percent of species group	Diameter(cm)>				
		20-39	40-49	50-59	60+	Total
		---------- *m^3/ha* ----------				
Red Seraya		9.4	3.1	3.5	10.8	26.8
White Seraya		3.5	1.1	1.6	6.9	13.1
Melapi		0.5	0.1	0.2	0.3	1.0
Yellow Seraya		0.6	0.1	0.2	0.8	1.7
Subtotal Light Hardwood	32	14.0	4.4	5.5	18.8	42.7
Kapur		2.1	0.6	0.9	2.8	6.4
Keruing		2.4	0.7	1.1	2.7	6.9
Subtotal Medium Hardwood	10	4.5	1.3	2.0	5.5	13.3
Selangan		1.0	0.3	0.4	0.5	2.2
Selangan Batu		0.8	0.2	0.5	2.0	3.5
Resak		0.6	0.1	0.1	0.3	1.1
Subtotal Heavy Hardwood	5	2.4	0.6	1.0	2.8	6.8
TOTAL DIPTEROCARP	47	20.9	6.3	8.5	27.1	62.8
Non-Dipterocarp Comm.	19	12.3	2.8	2.6	7.5	25.2
Other Species Non-Comm.	27	28.4	4.6	2.3	1.9	37.2
Pioneer Species	7	5.4	1.5	1.0	1.7	9.6
NON-DIPTEROCARPS	53	46.1	8.9	5.9	11.1	72.0
Subtotal Commercial	65	33.2	9.1	11.1	34.6	88.0
Subtotal Non-Commercial	35	33.8	6.1	3.3	3.6	46.8
Grand total	100	67.0	15.2	14.4	38.2	134.8
% Distribution by diameter class		50	11	11	28	100

Source: 1995/96 Sabah Forest Department Inventory-NBT Block Yayasan Sabah Concession (430 plots). Sampling Error (95 percent)+/-12.74 m^3.

Table 3.—*Estimated gross and net recoverable timber and pulpwood volumes from the 1995/96 Sabah Forest Department Forest Inventory of North Borneo Timber (NBT) block of the Yayasan Sabah Forest Concession*

Timber/Pulp size classes	*Gross volume*	*Net recovery volume*
Commercial Species>40 cm dbh[1]	54.8	43.8
Comm. & Non-Comm.< 40 cm dbh[2]	67.0	40.2
TOTAL	121.89	84.0

[1] *Timber vol. reduced by 20 percent to account for waste, decay, breakage, etc.*

[2] *Pulpwood vol. reduced by 40 percent to account for non-pulpable species, breakage, waste, etc.*

Annual Harvest Area and Volume by Species and Size Classes

The area to be cleared and planted in each of the 10 annual working blocks is identified on the project plan maps. The estimated yield volume from each of these annual working blocks is summarized by species and size classes in table 4. It should be noted that areas classified as Virgin Jungle Reserve (VJR) are not included in these estimates.

Field Sampling Design

Continuous Linear Sample Plots

A series of linear sample plots was established as "training sites" to correlate data from field sampling with future remote sensing data of the training sites. The sample plots consisted of surveyed lines, along which trees within 25 m on either side of the line were measured and plotted. The position, species group, diameter class, and crown width of all trees with with diameters greater than 20 cm were recorded.

Allocation of Field Samples by Timber Stand Type

The sample plots were allocated within four of the five timber stand classes. No field samples were established in the very low stand density class because there is no commercial timber in these stands. A total of 13.75 ha of sample plots was established, representing about 0.01 percent of the Benta Wawasan plantation area.

Field samples were allocated across a range of slope and elevation classes encountered on the project area. The length (m) and (ha) of sample plot, and the total area and estimated volume of each stand type were estimated.

Field Sampling Team Organization

Field sampling teams consisted of 2 to 3 people: a forester/crew leader, dendrologist, and a surveyor/mapper.

Field Sampling Productivity and Intensity

The daily productivity of the field sampling team was 350 m of 50-m-wide survey line (1.75 ha per day). During a 1-week survey period, 2,750 m (13.75 ha) of linear sample plot was established, representing 0.01 percent of the 106,000-ha project area.

Location of Sampling Units

The starting points of the linear sample plots were located at points along roads to reduce non-productive travel time to the sample areas, and to mark the start of each sample line clearly on the road, so that it can be located and referenced to the remote sensing survey flight lines. Subsample plots(1 per 10 ha) were established at intervals of approximately 100 m along the main sample line to measure smaller diameter trees (20 to 30 cm dbh), suitable for pulpwood. A total of 30 subplots was established.

Establishment of Field Sample Plots

A forest crew established and marked the start of linear sample plot line at a visible point along a logging road. A criterion for the establishment of this point was that it must be visible from the air so that it can be located and used as a point of reference for the airborne remote sensing flight lines of the field plots. The survey team located the center line of the sample plot line. Plot boundaries were established 255 m each of the sample

Table 4.—*Field sample allocation by timber stand classes*

Timber stand class	Estimated yield	Area	Estimated volume	Total extent of sample plots Length	and Area
	m^3/ha	ha	m^3	m	ha
Very high	60	4,626	277,560	850.00	4.25
High	40	5,326	213,040	950.00	4.75
Medium	20	17,489	349,780	600.00	3.00
Low	10	23,763	237,630	350.00	1.75
Very low	5	55,106	275,530	NA[1]	NA
Total		106,310	1,353,540	2,750.00	13.75

[1] NA = No plots available.

line. Within this linear sample plot, the location, diameter, stem height, crown width, and species of all trees >30 cm dbh were measured and recorded. One-tenth hectare subsample plots were established at intervals of 50 m along the sample line to enumerate trees suitable for pulpwood (20 to 30 cm dbh).

Field Sample Measurement

a. For larger trees, including:

- Dominant and co-dominant trees whose crowns occupy the forest canopy.
- Trees in 30 to 40 cm; 40 to 50 cm, and >60 cm dbh classes.

The following parameters were measured and recorded for all trees within 25 m of the sample line:

- Tree species
- Tree position (in relation to the surveyed line)
- Diameter at breast height (cm)
- Commercial stem length (m)
- Crown width (m)

b. For smaller trees, including:
- Understory trees
- Sapling and pole sized trees suitable for pulpwood
- Trees in the 20-30 centimeter diameter at breast height class

The trees were enumerated according to three broad species groups-dipterocarps, non-dipterocarps, and pioneer species—on one-tenth hectare subsample plots (20 m along sample line by 25 m each side of sample line).

RESULTS AND DISCUSSION

Field Sampling (Ground Truthing)

Results of the field samples are summarized in the following paragraphs. Table 5 contains summary description of the field sample plots, trees per ha by species group and tree size classes, as well as preliminary estimates of timber and pulpwood volumes per ha.

Tree Stocking by Timber Stand Density Class

The number of trees per ha (>20 m dbh) ranges from 58.5 trees per ha in areas of low stand density to 92.6 trees per ha in areas of high stand density. No field samples were undertaken in areas of very low and very high stand density.

Tree Stocking by Species Group

The percentage of trees of commercial species differed considerably between stand density classes, ranging from 46 percent of the trees enumerated on Transect 2 (low stand density class) to 81 percent of the trees enumerated on Transect 4 (high stand density class).

On average, 81 trees (>20 cm dbh) of commercial trees species were enumerated per hectare, representing 65 percent of trees sampled, with 35 percent being trees of pioneer species.

In the commercial species group, trees of the botanical family Dipterocarpus predominated, representing 56 percent of the trees of commercial species. Tree of other, non-Dipterocarp species made up the remaining 44 percent of commercial tree species.

Tree Stocking by Tree Size Class

Trees of commercial timber size (> 40 cm dbh), represented 43 percent of the trees enumerated, while smaller trees (<40 cm dbh), suitable for pulpwood, accounted for 57 percent of the growing stock.

The field sample indicated a higher concentration of large trees in areas classified as having high and medium stand density. For example, Transect 4 (high stand density) has the highest concentration of large trees, with 30 trees >50 cm dbh per ha, compared to 20 large diameter trees per hectare in the medium density class (Transect 3) and 12 to 14 trees per ha in the low density class (Transect 1 and 2).

Estimates of the timber and pulpwood volume per hectare were compiled from the tree species and size information discussed above. It was assumed that only trees of commercial species and size (>40 cm dbh) trees could be included in the commercial tree volumes. Small diameter (<40 cm) trees of all species would be available for pulpwood. In the absence of tree volume data at the time this paper was prepared, a rough calculation of volume was made, based on the following assumed net recoverable tree volumes per tree for each of the five diameter classes :

- 20-30 cm dbh class - 1 m^3 per tree
- 30-40 cm dbh class - 2 m^3 per tree
- 40-50 cm dbh class - 3 m^3 per tree
- 50-60 cm dbh class - 4 m^3 per tree
- 60 cm + dbh class - 5 m^3 per tree

Table 5.—*Summary of results of 1997 field sampling Benta Wawasan forest plantation*

Parameter measurement	Transect Number 1	Transect Number 2	Transect Number 3	Transect Number 4	Total or Average
DESCRIPTION OF FIELD SAMPLE PLOTS (TRANSECTS)					
Timber stand class (as per 10-year working plan)	Low (5 m^3/ha)	Low (10 m^3/ha)	Med (20 m^3/ha)	High (40 m^3/ha)	
Note:Transect in low, med., and high stand density classes-not in very low and very high density classes					
Length (m)	950.00	850.00	600.00	350.00	2,750.00
Area (ha)	4.75	4.25	3.00	1.75	13.75
Time required (days)	3	3	1	1	8
TREES PER HECTARE BY SPECIES GROUP					
Dipterocarps	22.7	17.9	34.3	42.3	29.3
Non Dipterocarp	10.1	20.5	29.7	32.6	23.2
Subtotal Commercial	32.8	38.4	64.0	74.9	52.5
Percent Commercial	56%	46%	74%	81%	65%
Pioneers(pulp spp.)	25.7	45.2	23.0	17.7	27.9
	44%	54%	26%	19%	35%
Total all species group	58.5	83.6	87.0	92.6	81.1
	100%	100%	100%	100%	100%
TREES PER TRANSECT BY TREE SIZE (dbh)CLASSES					
20-29 cm	43	72	32	29	176
30-39 cm	124	156	109	52	441
40-49 cm	44	77	58	29	208
50-59 cm	26	20	23	20	89
60+ cm	41	30	39	32	142
Total all sizes classes	278	355	261	162	1,056
TREES PER HECTARE BY TREE SIZE (dbh)CLASSES (trees/ha)					
20-29 cm	9.05	16.94	10.67	16.57	13.3
30-39 cm	26.11	36.71	36.33	29.71	32.2
40-49 cm	9.26	18.12	19.33	16.57	15.8
50-59 cm	5.47	4.71	7.67	11.43	7.3
60+ cm	8.63	7.06	13.00	18.29	11.7
Total all sizes classes	58.53	83.53	87.00	92.57	80.4
ESTIMATED NET RECOVERABLE COMMERCIAL VOLUME PER HA BY SIZE CLASSES (m^3/ha)					
20-29 cm	5	10	6	10	8.0
30-39 cm	31	44	44	36	38.7
40-49 cm	12	20	34	32	24.7
50-59 cm	10	7	18	30	16.1
60+ cm	19	13	38	59	32.4
Total all species, all sizes	78	94	140	167	120
SUMMARY OF ESTIMATED YIELDS (m^3/ha) (based on field sample results)					
Comm.Sp.and sizes >40 cm dbh	42	40	90	121	68
Pulpwood sizes <40 cm dbh	37	54	50	46	39

Commercial timber volume included only commercial (Dipterocarp and non-Dipterocarp) timber species. To reduce the gross volumes from the sample estimates to net recoverable timber volume, the volume estimates from the field sample were reduced by 20 percent to account for waste, decay, and breakage during logging and transport.

Pulpwood volumes included all species in the 20- to 40-cm dbh classes. The estimated gross volume from the field sample estimates were reduced by 40 percent to account for non-usable species, breakage, waste, decay, and other losses during harvesting.

Using these assumptions and the improvised, preliminary per tree volume estimates, the average volume of all species and all sizes of trees is estimated to be 120 m^3 per ha, ranging from 78 m^3 per ha in low stand density areas to 167 m^3 per ha in high stand density areas (table 5).

This volume conforms to the gross volume of commercial timber trees (>40 cm dbh) and pulpwood (<40 cm dbh) indicated in the Sabah Forest Department's 1996/97 Forest Inventory of the NBT Block which indicated a gross volume of commercial timber and pulpwood of 121.8 m^3 per ha (table 3).

The commercial timber volume (tree >40 cm dbh) is estimated to be 40 m^3 per ha in the low stand density class (Transect 1 and 2), which accounts for most of the plantation area. Timber volume per hectare for the medium stand density area (Transect 3) is estimated to be 90 m^3 per ha, and for the high stand density class (Transect 4), 10 m^3 per ha. It should be noted that the area of high density stands is relatively small (table 5).

It is estimated that an average of 39 m^3 of pulpwood can be recovered from trees of all species in the 20- to 40-cm dbh classes. The highest pulpwood volume occurs on Transect 2 (low stand density) where a large number of small diameter trees contribute to a pulpwood volume of 54 m^3 per ha. On Transects 1, 2, and 4, pulpwood volume averages 40 m^3 per ha.

CONCLUSIONS

- The stratified field sampling technique of inventory assessment confirmed that the timber volume on the Benta Wawasan plantation area is similar to that indicated by the 1995/96 Sabah Forest Department Forest Inventory of the North Borneo Timber (NBT) Block.

- Based on this preliminary analysis and compilation of data from the stratified field sampling, the volumes of timber and pulpwood on the Benta Wawasan plantation area appear to conform to the Stock Table from the 1995/96 Sabah Forest Department Inventory. Both sources indicated about 120 m^3 per ha of standing volume of commercial timber trees (>40 cm dbh) and small diameter pulpwood (< 40 cm dbh).

- The standing volume indicated by these sources is much higher then the volumes indicated in the 10-year working plan for the Benta Wawasan Forest Plantation Project, which range from 5 m^3 per ha to 60 m^3 per ha.

- On most of the areas (areas of low to medium timber stand density), the estimated net recoverable volume in large trees (>40 cm dbh) of commercial timber species is expected to average 40 m^3 per ha. On limited areas, where timber stand densities are high, the volume could be as high as 100 m^3 per ha. This confirms estimates based on the Sabah Forest Department Inventory, which indicated a net recoverable timber volume of 43.8 m^3 per ha (tables 3 and 5). The estimated average net recoverable pulpwood volume is 39 m^3 per ha. This confirms estimates based on the Sabah Forest Department Inventory data, which indicate a net recoverable pulpwood volume of 40.2 m^3 per ha.

LITERATURE CITED

De Gier, A.; Sakouhi, A. 1995. Woody biomass mapping using field data and SPOT satellite imagery. Paper presented at the Forest Resource Inventory and Monitoring Subject Group S4.12-00, Remote Sensing Technology, IUFRO XX World Congress; 1995 August 6-12; Tampere, Finland. 7 p.

Kohl, M. 1996. Multi-phase sampling schemes for extensive forest surveys in tropical forest. In: New thrusts in forest inventory, EFI Proceeding, No. 7: 69-79.

Kamaruzaman Jusoff. 1998. Incorporating remote sensing/FIS technology in forest and tree resources. Poster paper presented at the 27th International symposium on remote sensing of the environment; 1988 June 8-12; Tromso, Norway. 6 p.

A Comparison of Periodic versus Permanent Surveys

Michael Köhl and Charles T. Scott

Abstract.—Extensive forest surveys can be periodic or permanent, regional or national, can include midcycle updates or not, or use partial replacement of plots or not. Fifty-two combinations of these and other factors were evaluated, not solely on a statistical basis, but also on their perceived ability to meet various design and customer objectives. These criteria include survey cost, precision and reliability of the results, reporting and customer satisfaction, simplicity, and flexibility. Based on this evaluation of permanent and periodic surveys, we recommend that planners compare their current periodic design to a permanent national design, a permanent regional design, and each of the two with a midcycle update.

The objectives of forest surveys can differ considerably, so various sampling designs and assessment methods are applied. Comprehensive and sensitive monitoring of forest condition is needed to assess environmental effects on forest ecosystems and to ensure the sustainability of those ecosystems. Forest inventories carried out on one single occasion are justified only in rare cases, such as reconnaissance surveys. Monitoring forests demands repetitive assessments over time and remeasurement of sample plots and sample trees.

The time period between assessments and the allocation of sample plots are two important issues in monitoring. Statistical designs for sampling on successive occasions, such as Continuous Forest Inventory (CFI) or Sampling with Partial Replacement (SPR), have been described in the framework of periodic assessments with sampling occasions following, for example, the management planning cycle. The advantage of periodic assessments is the common point in time to which the inventory results can be related.

In extensive surveys, the periodicity of assessments has some major disadvantages: the number of staff members is substantially higher during the field assessment periods, within an inventory cycle there are periods with both very high and very low workloads, expertise can be lost due to the unevenly distributed tasks, and the annual budget is not constant. The organization of periodic assessments has to be flexible to the varying tasks to be accomplished within each year.

From an organizational point of view, permanent assessments are superior to periodic assessments; in the former, a (constant) proportion of the total number of sample plots is visited each year. Many national forest inventory systems including those in Austria, Finland, France, Sweden, and the US have adopted permanent surveys (table 1). In some countries, the assessment of the annual proportion of plots is conducted region by region (e.g., Sweden and France); in others an annual subsample covering the whole country is taken (e.g., Austria) (EC 1997).

The classical sampling and estimation methods, which have been developed mainly for periodic assessments, have to be adjusted for permanent surveys. One major consequence of applying a permanent survey system is the necessity to update the plot and tree data assessed in different years to one common point in time. This can be done by modifying the CFI and SPR procedures, by introducing estimation methods such as the Kalman filter or Mixed Estimator (ME), which can incorporate updating and projections using growth functions.

The objective of this paper is to present and compare design alternatives for permanent and periodic surveys. This study was initiated by the Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland, to evaluate design alternatives for the third Swiss National Forest Inventory (NFI). We therefore present the evaluation of design alternatives for the example of the Swiss NFI.

SAMPLING METHODS

Many sampling design options exist for both periodic and permanent forest surveys. For each of these designs, there are several possible estimators. Each of these combinations has different cost-effectiveness, level of complexity, and utility. There are three primary sampling methods used in extensive (large-scale) forest surveys.

Chair of Forest Biometrics , Institute for Forest Growth & Computer Science, Dresden University of Technology, Tharandt, Germany; Project Leader, Northeastern Research Station, USDA Forest Service, Delaware, OH, USA.

Table 1.—*Mode of surveying for several European national forest inventories*

Country	Time since first inventory (years)	Inventory period	Assessment scheme	Regional or partial assessments
Austria	30	1986-1990	continuous	fraction of entire area
Finland	70	continuous	by regions	(5-year cycle)
France	20/ 30*	1980-1993	continuous	by region (10-12 year cycle)
Germany	-	1986-1990	periodic	
Italy	-	1985	periodic	
Norway	70	1986-1993 since 1994	continuous continuous	by region fraction of entire area
Sweden	70	1988-1993	continuous	fraction of entire area
Switzerland	10/30*	1983-1985 1993-1995	periodic periodic	

* for some limited areas

Continuous Forest Inventory

The permanent observation of forests has a long tradition, but sample-based forest surveys are a rather recent concept. Stott (1947) introduced a design for sampling on successive occasions called Continuous Forest Inventory. CFI uses a set of permanent sample plots, which are established at the first occasion and remeasured at each successive occasion. CFI plots are selected either randomly or systematically. Plots are monumented, so that they can be measured on future occasions. Estimates are easily obtained with CFI and are particularly good for change estimation. The estimation procedures are simple and results are easy to understand. Additive tables are obtained, where independent estimates of cell values sum up to the row and column totals. Even for more than two occasions, the estimation procedures are clear.

Sampling with Partial Replacement

Sampling with Partial Replacement was introduced into forestry by Ware and Cunia (1962) based on work by Patterson (1950). At the first occasion, assessment and estimation procedures are the same as with CFI. At the second occasion, only a portion of the plots established at the first occasion are remeasured and a set of new plots is added. The remeasured plots are used to develop regression relationships to update all unremeasured plots. A second estimator is based on the new plots. Both estimates are combined and result in more precise estimates of current values than does CFI (Scott 1984). The emphasis can be altered between the estimation of current values and change detection by adjusting the proportion of new and remeasured plots; thus SPR is simultaneously cost-effective for estimates of current values and net change in those values.

Scott (1986) described many of the problems encountered with SPR. One of the major disadvantages is the complexity of the design arising from the number of plot types, which increases geometrically with the number of occasions. The complex estimation procedures become very unwieldy for more than two occasions. SPR estimators can be applied to independently estimate individual row and column cells of tables, as well as row and column totals. However, data developed in this way are not additive; cells will not sum to row and column totals.

Double Sampling

SPR and CFI were originally described as single-phase inventory systems using only field assessments. The desire to increase the cost-efficiency of surveys has led to the development of design alternatives that combine field measurements with auxiliary information mainly obtained by remote sensing techniques. Double-sampling designs include information from two different assessment levels. Double sampling for stratification is a derivative of stratified sampling and is used when the stratum sizes are unknown. To estimate the stratum sizes, a large first-phase sample is drawn. On each of these sampling units, only the stratum in which it falls is recorded. The stratum sizes are estimated as the number of first-phase sampling units falling within each stratum. In forest surveys, aerial photographs are often used to locate and classify the first-phase sample. This stratification on photos can usually be done at a fraction of the cost of ground observation.

Double sampling for stratification can be used to increase the cost-efficiency of sampling on successive occasions. Köhl (1994) describes the sampling design of the second Swiss national forest inventory, which is a combination of SPR and double sampling for stratification and uses CFI-type estimators for current values and change. Scott and Köhl (1994) give estimates for SPR and stratification for up to three occasions and discuss the complexity of estimation.

Periodic Survey Designs

Most countries started with a periodic survey system and have already conducted several cycles of their national forest inventories (NFI). Periodic survey designs are characterized by field assessments conducted across the whole country once every cycle. In spite of the fact that the measurement usually requires more than 1 year to complete, the information is regarded as relating to a single point in time. In Europe, countries such as Germany, Switzerland, and Italy are practicing periodic surveys, while Switzerland is one of the very few countries that has a permanent NFI setup, but it is still applying a periodic survey design.

Permanent Survey Designs

Among the countries having a permanent NFI setup and applying a permanent inventory system are Austria, Finland, Sweden, and the US. The following brief description of their inventory systems is intended to give insight into the multitude of applied inventory systems.

In Finland, a permanent survey design with regional assessments was implemented. The eighth inventory cycle was conducted between 1986 and 1994. Only temporary plots were measured until 1992. Since then permanent plots are being established, so that in the inventory regions of North Finland, 20 percent of the sample plots are permanent. No updating techniques are applied to derive current forest resource results. Estimates of change are obtained by comparing total values and means of two successive occasions as well as analyzing increment cores. In 1990, a special investigation was carried out. Plot data were updated to a common point in time by combining modeling techniques for estimating increment and natural loss, with information on removals from auxiliary sources. In the forest health monitoring program, 3,000 plots distributed over the entire country were assessed twice (1986 and 1990) and were being remeasured a third time in 1995. However, they are not used for updating purposes in the scope of the forest resource assessment.

Permanent surveys with annual national assessments are carried out in Austria and Sweden. The Austrian national forest inventory shifted in 1980 from a 10-year cycle to a 5-year cycle. One-fifth of the entire set of plots is assessed annually at the national level. Due to the short inventory cycle, no updating is applied. To ensure consistency in the estimates of net change, plots are remeasured at approximately the same point during the growing season. Before 1980, estimates for increment were obtained by the analysis of increment cores. Since then, change is estimated by comparing data from two successive occasions.

The Swedish national forest survey established the first permanent clusters between 1983 and 1987 and remeasured them for the first time between 1988 and 1992. During the remeasurement period, temporary plots were also measured. The number of permanent and temporary plots was equal each year. In 1993, budget cuts forced the shift from a 5-year to a 10-year remeasurement cycle. However, the number of temporary plots measured each year will be the same as in the inventory period between 1988 and 1992. When results for the entire country are estimated, the changes observed on permanent plots are used to update the older data from temporary plots. Changes are computed by a mixed approach. On permanent plots, the differences between two occasions are taken to calculate net change; on temporary plots, growth is estimated by the analysis of tree ring cores. For long-term timber forecasts, the so called Hügin system is applied, in which trees from temporary plots are updated using matching trees from remeasured plots.

In the US, the Forest Inventory and Analysis (FIA) units of the USDA Forest Service have been conducting permanent regional surveys since the 1940's. These surveys are typically conducted on a state-by-state basis within each region on a cycle of 5 to 15 years. Although some units have used SPR, most plots are permanent. Double sampling for stratification is used at each measurement using current aerial photography. Most units do not update values between occasions, but midcycle update surveys (Scott 1979) have been conducted in special cases. For national assessments, various techniques have been used to update the estimates to a common date.

The USDA Forest Service and the Environmental Protection Agency, in cooperation with other agencies and states, have been conducting the Forest Health Monitoring (FHM) program since 1990. The purpose of the program is to provide a mechanism for detecting widespread change in forest ecosystems due to human and natural disturbances. The design uses a fixed grid across the entire US, with one ground plot every 62,500 ha. However, one-fourth of the grid is measured each year with the rest of the grid being measured in the succeeding years. Thus, plots are remeasured on a 4-year cycle. This interpenetrating or rolling survey design is expected to provide precise estimates of change after the first 4 years.

There is a strong interest in the US in providing forest resource data more frequently than is currently provided by FIA but with more detail than can be provided by FHM. Research is being conducted by the North Central and Southern FIA units on sampling a portion of all states each year and combining this with remotely sensed data to provide timely estimates with adequate levels of detail annually.

ESTIMATION METHODS

Many methods exist for developing estimates from a sample design. Simple means and variances are appropriate for the CFI design. Typically, the more complex regression estimators are used for SPR, but the CFI estimators can also be applied. This results in a loss of precision but a gain in simplicity.

One way to improve estimates in successive surveys is to use the Kalman Filter (Kalman 1960). It was developed for time-series data and adapted for forest surveys by Dixon and Howitt (1979). They showed that it simplifies to the SPR estimator when no control information was used, or any prior information. It is a recursive estimator, in that the estimates at time t are developed by first estimating values at time 2 based on time 1, then time 3 based on time 2, etc.

A related method is the Mixed Estimator (Theil 1971). The regression or Generalized Least Squares (GLS) approach is used for the sample data. When prior information in the form of growth models is available, then using them can improve the sample-based estimates. The sample data and the model predictions are then set in a single estimation framework to provide more precise resource estimates (Van Deusen 1996).

One of the difficulties with each of the estimators, except the CFI estimator, is the lack of additivity of tables. By this, we mean that if the estimators are applied to each cell in a table and to the table margins, the rows and columns will not sum to the margins. Although this results in precise estimates for each cell independently, users do not like or understand this characteristic (Scott 1986). A method of addressing this problem was introduced by Schreuder *et al.* (1988). However, a more direct and simple means is needed for large-scale, repetitive surveys.

UPDATING AND PROJECTION USING GROWTH FUNCTIONS

Users of forest resource data want precise estimates frequently. One method of providing this information frequently is to update the survey data without further field sampling.

One simple alternative for producing estimates for succeeding years after a survey is to use the same results without modification. However, this results in estimates with some (unknown) bias. If the survey results were precise to begin with, then the mean squared error (bias squared plus variance) may be preferable to other alternatives. A second approach is to update the data based on past rates of change, such as using the SPR regression estimators to predict future change. A third approach is to use growth and yield models. Both of the modeling alternatives introduce prediction errors and, perhaps, model errors if the model is not applicable to the survey data. This holds especially true if growth of uneven-aged mixed species stands has to be modeled.

Growth and yield models are typically developed for commercial tree species to predict individual tree or stand growth and standing volume at some point in the near future. Some models have been developed for survey applications, rather than forest management planning. One such model is TWIGS (Belcher *et al.* 1982), which was initially developed in the Central United States using both inventory and silvicultural research data. In this way, all tree species present in the region can be modeled. Prediction intervals are usually 1, 5, or 10 years. Many models also have components to predict mortality and ingrowth, and can be used to manipulate harvest levels. Hansen (1990) used TWIGS to update unremeasured plots in an undisturbed stratum, which was then combined with a complete remeasurement of the disturbed stratum.

In forest resource surveys, there is at least as much interest in the rates of change as in the current values. Although net change between surveys is helpful, ingrowth, accretion (survivor growth), mortality, and harvest levels provide a more useful picture. While temporary surveys can provide estimates of net change, only remeasured plots can provide estimates of the components of change. Van Deusen (1989) has described the estimation of these components in an SPR context.

DESIGN CRITERIA

A host of possible alternatives are available in the planning of an extensive inventory on successive occasions. From the viewpoint of the inventory planner, the design alternatives include several sample selection rules, sample sizes, and the use of additional information, e.g., from maps or aerial photographs. We identified seven characteristic properties of possible sampling alternatives. Those properties form the framework within which the most appropriate alternative is to be found.

1. **Mode of inventory**. An inventory can be permanent or periodic.
2. **Allocation of sample plots**. A permanent inventory means that part of the entire sample is surveyed annually. These samples can be distributed over the entire nation or by region.
3. **Subsample**. In addition to the annual survey of one region or the entire nation, other subsamples could be surveyed. In regional surveys, for example, a national subsample could be surveyed annually.
4. **Several subsamples**. Just as one network of plots can be allocated nationally or regionally with a specified remeasurement period, a second network can be established that has a different combination of allocation rule and measurement period. For example, one annually surveyed sample plot network could be used for the estimation of some few key attributes. And a second network, including larger sample sizes, could be surveyed at intervals of several years, which serves for interim reports at the national level.
5. **Mode of inventory for the subsamples**. Each subnetwork can be surveyed annually or periodically.
6. **Allocation of the subsamples**. Each subnetwork can be surveyed at a regional or national level.
7. **Permanent samples or partial replacement of samples**. Each network or subnetwork can be based either exclusively on permanent inventories or on replacing some plots with new ones.

The specified seven design properties were combined to determine possible sampling alternatives for both periodic and permanent survey designs in the scope of the third Swiss NFI. Figure 1 shows the possible combinations of the seven design properties as well as the resulting sampling alternatives. Some of the possible combinations are not practicable and are not shown.

COMPARISON FACTORS

To select the optimal design among the alternatives, clear evaluation criteria have to be given that involve a variety of perspectives, such as statistical, logistical, economic, and political information needs. Precision, cost, and cost-efficiency are three well-known evaluation criteria. For each alternative, there exists an optimal combination of sample sizes, which can be defined in one of two ways: minimizing the cost for a fixed precision level, or minimizing variance for a fixed cost. To compare different design alternatives, they must either reflect the same amount of cost or result in the same level of precision. However, the evaluation should not be based on cost-efficiency alone, but should involve other criteria. Beside costs, the criteria are accuracy and reliability, customer satisfaction, simplicity, and flexibility. Projection and updating issues have a decisive impact on the survey design and should be included in the evaluation process.

The suitability of the various design alternatives can be investigated with respect to the comparison factors described above. To clarify the evaluation process, the possible design alternatives given in figure 1, i.e., the sampling design alternatives for the third Swiss NFI, are used.

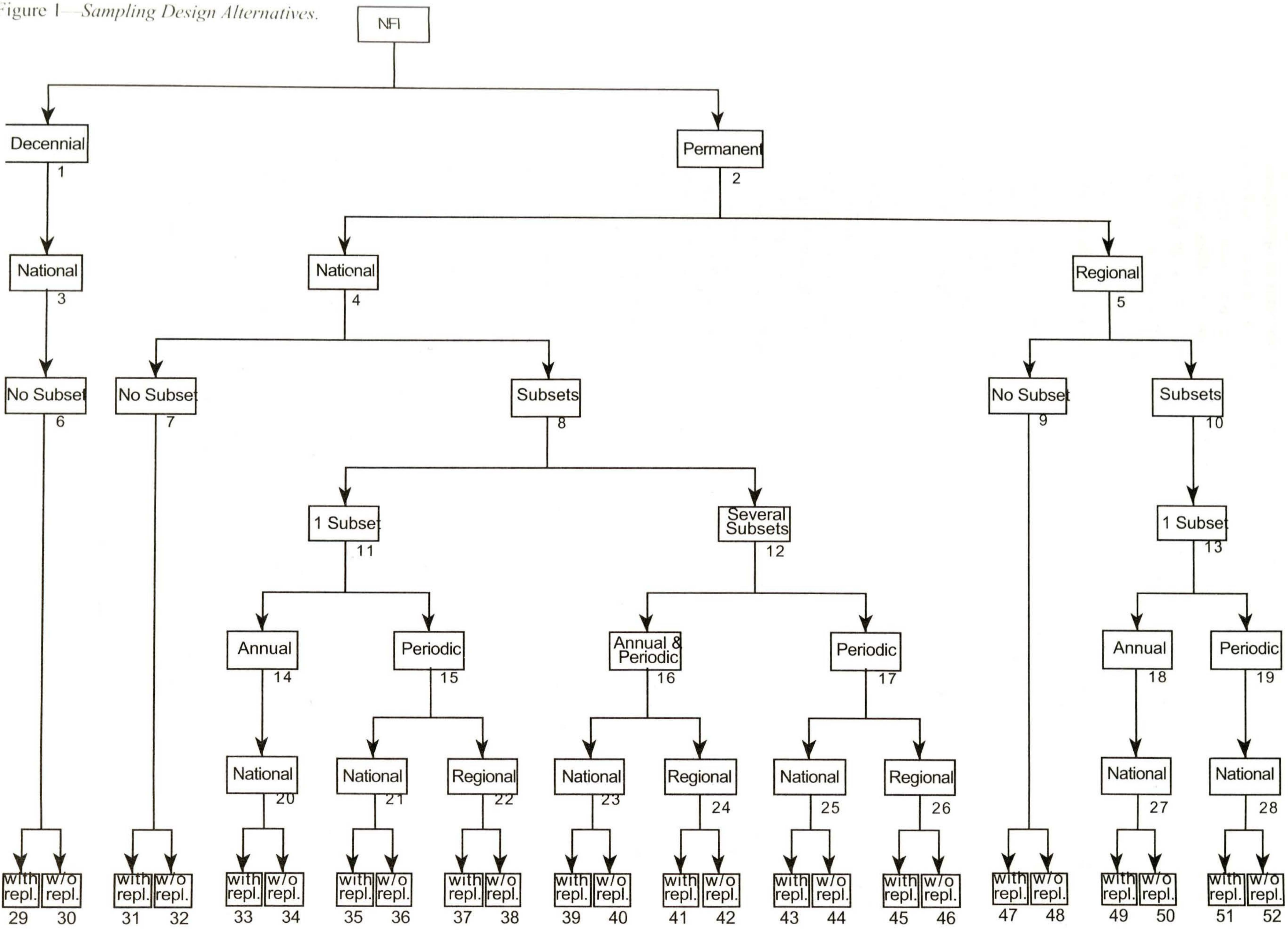
Costs of the Inventory and Organization

Permanent inventories are preferred to periodic ones based on their even budgets over time. Startup costs are reduced and the experience of the staff is maintained, which results in increased productivity. Permanent regional surveys are preferable, because the field appraisals and (unproductive) travel is concentrated in a smaller area. Subsamples raise the complexity of the procedure and reduce the productivity, especially if they are spread over the whole country. If plots are well monumented, productivity is also increased if only permanent samples are used. In view of the inventory costs and the organization, a permanent, annual, regional survey without subsamples with no replacment seems to be the most suitable alternative (fig. 1, alternative 48).

Accuracy and Reliability

No inventory is beneficial unless it is accurate (low bias and small sampling errors) and reliable (procedural and computational errors are avoided and the survey regarded as trustworthy). Permanent surveys are preferred because expertise is retained. Regional surveys without subsets are preferred, because their simplicity makes them more reliable. Some design alternatives may necessitate the development of growth models to update the values of previously measured sample plots to the current time, which can greatly improve precision. However, this dependence makes the estimation procedures more sophisticated and may lead to reduced reliability. Some sample plans are more robust against the occurrence of errors than others, e.g., methods that replace old sample plots by new ones, avoiding reliance on a single unrepresentative sample. However, using complex SPR estimators with them may come at the cost of reliability, because their regression estimators can be influenced by outliers. A permanent NFI with annual, regional surveys without subsamples, but with the replacement of permanent samples by new samples, seems to be the most appropriate alternative for accuracy and reliability (fig. 1, alternative 47).

Figure 1—*Sampling Design Alternatives.*


NFI
Decennial
1
Permanent
2
National
3
National
4
Regional
5
No Subset
6
No Subset
7
Subsets
8
No Subset
9
Subsets
10
1 Subset
11
Several Subsets
12
1 Subset
13
Annual
14
Periodic
15
Annual & Periodic
16
Periodic
17
Annual
18
Periodic
19
National
20
National
21
Regional
22
National
23
Regional
24
National
25
Regional
26
National
27
National
28
with repl.
29
w/o repl.
30
with repl.
31
w/o repl.
32
with repl.
33
w/o repl.
34
with repl.
35
w/o repl.
36
with repl.
37
w/o repl.
38
with repl.
39
w/o repl.
40
with repl.
41
w/o repl.
42
with repl.
43
w/o repl.
44
with repl.
45
w/o repl.
46
with repl.
47
w/o repl.
48
with repl.
49
w/o repl.
50
with repl.
51
w/o repl.
52

Publication of the Results and User Satisfaction

A main drawback of periodic inventories is the long time between reports. However, annual reports in permanent national inventories may be too frequent and too imprecise. Permanent regional surveys permit periodic reports at regional and national levels, thus meeting the needs of local and national user groups. Efficient and unbiased estimates can be generated for each cell in a table, but some designs lead to estimators that do not add to the estimate of the table total. Many users will not see such tables as credible. Complete remeasurement is preferred, because it provides better estimates of change and is easier to understand. Three designs that perform well in this category:

permanent regional survey with periodic national reports (fig. 1, alternative 52)
permanent national survey with periodic national reports (fig. 1, alternative 21)
permanent national survey with periodic regional reports (fig. 1, alternative 22)

The key is to provide analytical results periodically and at both the regional and national levels, accomplished through the use of subsamples. This result differs greatly from that for the other factors.

Simplicity and Plausibility

Either a periodic inventory at a national level or a permanent inventory at a regional level are to be favored for reasons of simplicity and plausibility. Subsamples should be avoided. The simple CFI estimation procedures can be used both at national and regional levels. The exclusive use of permanent samples promotes the simplicity and plausibility of the inventory design. The preferred method is a CFI design at the regional or national level (fig. 1, alternatives 1 and 48).

Flexibility

Permanent inventory methods are more flexible than periodic ones, because changes and additions to the list of attributes to be assessed are possible each year. Regional surveys can be adapted to the regional (local) requirements. Subsets can provide opportunities to be flexible, but there are disadvantages due to the added complexity. Thus, a permanent, regional inventory without subsamples is preferred for flexibility (fig. 1, alternative 9).

FOUR SELECTED INVENTORY ALTERNATIVES

In summary and in consideration of the advantages and drawbacks of the design alternatives to be favored under various aspects, it becomes obvious that a permanent, regional survey without subsamples and with the exclusive use of permanent sample plots (fig. 1, alternative 48) is preferable to the other design alternatives. If, however, individual comparative factors are weighted stronger than others, other design alternatives might be more suitable for the third Swiss NFI. Hence, four design alternatives are described in the following. Each of the four alternatives can be implemented with or without the replacement of sample plots.

Alternative 1: Periodic National Survey

This design alternative corresponds to the current Swiss NFI design. Sample plots spread over the whole country are assessed once during the inventory cycle (at present 10 years) (fig. 1, alternative 29 or 30). Each measurement requires 3 years to complete. Subsamples are not used.

The design lacks constancy in its annual budget, so it ranks poorly in cost. Due to its simplicity, the design is easy to understand, leads to additive tables, and allows for regional or national survey results. The evaluation procedures are clear even after several measurement cycles, and the design is regarded as reliable and robust. Disadvantages are that the experience gained by the staff, especially that of the surveying crew and computer scientists, is lost between surveys. New attributes can be added only every decade, and the production of interim reports is not possible. The actual design of the NFI is a design of contradictions. For many aspects, it ranks at the top, but for costs, flexibility, and continuity of the efforts, it has clear deficiencies.

Alternative 2: Permanent Regional Survey

The permanent regional survey is much the same design as the periodic national survey, but the country is divided into regions, each containing approximately 1/10 of the samples of the second Swiss NFI. This is accomplished by combining cantons, i.e., federal states. Ideally, the survey of each region can be concluded within 1 year. Hence, the inventory cycle for the national survey corresponds to the current 10-year cycle. Subsamples are not used; however, the forest damage survey could be used for interim reports. In figure 1, the procedure corresponds to alternative 47 (with replacement) or alternative 48 (exclusively permanent sample plots).

The method is efficient and appears to have relatively simple estimation procedures and a favorable cost structure. It leads to reliable results with low estimation errors and can easily be adapted to regional peculiarities and demands. Regional events, such as wind damage, can be readily assessed with this design. It seems to be less favorable, however, for national purposes. The time between surveys is still long (10 years) for an individual region. Changes to the attributes likewise requires 10 years to complete at the national level. Thus, this alternative is especially suitable to meet regional information demands. But for most of the questions raised nationally, this concept is less appropriate.

Alternative 3: Permanent National Survey with a Periodic National Update

The third alternative differs considerably from the two alternatives already introduced. A fixed percentage of all sample plots of the NFI is surveyed each year. If a 10-year cycle is used, 10 percent of the samples would be measured each year. These samples will be spread over the country, forming 10 different sample sets that will be surveyed independently of one another. Every year new estimates of the current status and change can be calculated. However, the low number of sample plots measured in the current year results in relatively high sampling errors. A subsample that is more often assessed, e.g., every 5 years, could be used to improve the statistical properties of the design. The more frequently assessed subsample could be used to update the rest of the plots to a common date and would facilitate national reports of higher estimation accuracy. Thus, the method corresponds to a variation of SPR but increases the complexity of the survey accordingly (Scott 1986, Köhl 1994) (fig. 1, alternative 36). New samples can be added (fig. 1, alternative 35) without greatly increasing the complexity of the procedure.

With this alternative, new attributes are easily and rapidly introduced. The distribution of the effort is nearly constant. Because national results are more frequent, the expected satisfaction of the users is greater than in the first or second alternative. However, travel costs are comparatively high, since samples are surveyed in the entire country each year. Because the estimation procedures are very complex due to the need to develop and use a growth model for updating, the evaluations are not easily understood, the tables are not additive, and it is doubtful whether the available samples and funding will achieve the accuracy of the first and second alternatives. And, it is difficult to change the inventory cycle in this procedure or to concentrate the sampling network on a specific region of interest.

Alternative 4: Permanent Regional Inventory with National Updates

With the Permanent Regional Inventory with National Updates design, one region is surveyed each year. After several years, instead of measuring one region, a group of samples distributed over the whole country are surveyed. Thus, the number of regions is reduced by the number of times during the cycle a national update is performed. In a 10-year inventory cycle with a national update every 5 years, the country would need to be divided into eight regions. By means of the national subsubsample, the regional surveys are updated to a common year. Thus, it is possible to produce results at a national level during the update years. Because this is an SPR design, it includes all the disadvantages and the complexity of partial replacement of plots. This procedure is shown in figure 1 as alternative 51 (with new samples) or alternative 52 (exclusively permanent samples).

The design proves to be cost efficient for estimating regional and national results. During the years when the national network is surveyed, the cost efficiency drops because of the higher travel costs. The calculation of regional results does not require any updating, hence the design is not very complex here. The evaluation of national results becomes complex, however, and results in nonadditive tables. To introduce new attributes at a national level requires a comparatively long time. This design has not been found to be distinctly superior or inferior to other design alternatives.

UPDATING OF THE INVENTORY DATA

Some of the design alternatives require updating inventory data to a common date. Updating procedures are based on projection models that can predict the current state. This implies the prediction of the individual tree history: ingrowth, mortality, cut, or survivor tree. Likewise, the increment of each survivor tree must be estimated.

The field measurement period for almost all national inventories in Europe covers several years. The necessity of relating the inventory data to a common date depends greatly on the field period. The problem of a common date is handled differently among countries. The field measurement period of the first German national forest inventory lasted from 1985 to 1990. The inventory data refer to a reference date, but the assessed data were not updated. Thus, indication of a reference date seems to be rather questionable, and is unjustifiable from a methodical point of view. The Swiss NFI does not specify a date that all data refer to. Until now, the inventory period consisting of several years has been generally accepted and the wish for a reference date has never been expressed by users.

The Swedish NFI provides results for 5-year periods. Since 1981, annual reports have been published that generally rely on data surveyed over the past 5 years. An updating of data is not performed at the national level (Söderberg 1986). A special technique of updating is used for regional estimates of the long-term use potential. The Hügin System substitutes recent data from comparable trees for missing data for unremeasured trees.

The STEMS projection system (Belcher *et al.* 1982) is used by the North Central Forest Inventory and Analysis unit in the United States. STEMS has much of the functionality of a growth and yield model but was developed for prediction of inventory data. It can be regarded as a regional model that can be applied to all tree species–not just to the commercial ones. However, it is not as accurate as forest growth models, because site and stand history data are missing or not as reliable as with long-term forest growth plots.

CONCLUSIONS

The combination of the specified seven properties of sample designs leads to many possible design alternatives for the forest inventories on successive occasions. The most appropriate design has to be selected on the basis of clear objective criteria. Depending on the weighting of the decision factors, different alternatives may be selected. Therefore, a robust, cost-effective design that meets most requirements should be selected. If the design is changed, additional efforts must be made to alter the estimation and publication procedures. Likewise, the impacts of an increase in the complexity of the design should not be underestimated.

In the search for an optimal inventory design and the appropriate estimation procedures, the increased requests for information on the non-productive functions of the forests should not be overlooked. Examples include criteria and indicators that quantify the sustainability and functions of the forest, or assessments of the protective function of forests. In general, these characteristics cannot be directly measured, rather they are recorded via definitions or deduced via models. Since objective data are not collected for this new group of characteristics, complex inventory designs make their inclusion more difficult.

ACKNOWLEDGMENTS

We are greatful for the helpful information about ongoing national forest inventories that was provided by Erkki Tomppo, Finnish Forest Research Institute, Helsinki; Klemens Schadauer and Karl Schieler, Forstliche Bundesversuchsanstalt, Vienna, Austria; and Wien and Bo Ranneby, Swedish University of Agricultural Research, Umeå. This study was funded by the Swiss Federal Institute for Forest, Snow and Landscape Research (WSL/FNP), Birmensdorf, Switzerland, and the USDA Forest Service, Northeastern Experiment Station. We want to express our thanks to all those, who made this cooperation possible, especially to Peter Brassel, WSL/FNP, head of the Swiss NFI, who supported our work generously and encouraged us in countless discussions.

We want to express our thanks to Berthold Traub, Swiss Federal Institute for Forest, Snow, and Landscape Research, Birmensdorf, Switzerland, and Vittorio Tosi, Range and Forest Management Research Institute, Villazzano, Italy, for reviewing the manuscript and for providing helpful comments.

LITERATURE CITED

Belcher, D.M.; Holdaway, M.R.; Brand, G.J. 1982. A description of STEMS—the stand and tree evaluation and modeling system. Gen. Tech. Rep. NC-79. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 18 p.

Dixon, B.L.; Howitt, R.E. 1979. Continuous forest inventory using a linear filter. Forest Science. 25(4): 675-689.

European Commission (EC). 1997. Study on European forestry information and communication system: report on forest inventory and survey systems. Luxembourg: Vol. 1 and 2. 1368 p.

Hansen, M.H. 1990. A comprehensive sampling system for forest inventory based on an individual tree growth model. St. Paul, MN: University of Minnesota. 256 p. Ph.D. dissertation.

Kalman, R.E. 1960. A new approach to linear filtering and prediction problems. Journal of Basic Engineering. 82: 34-45.

Köhl, M. 1994. Statistisches Design für das zweite Schweizerische Landesforstinventar: ein Folgeinventurkonzept unter Verwendung von Luftbildern und terrestrischen Aufnahmen. Mitteilungen der Eigdenössischen Forschungsanstalt für Wald, Schnee und Landschaft 69(1). Birmensdorf, Switzerland. 141 p.

Patterson, H.D. 1950. Sampling on successive occasions with partial replacement of units. Journal of the Royal Statistical Society. B 12: 241-255.

Schreuder, H.T.; Li, H.G.; Ryan, M.G.; Scott, C.T. 1988. Adjusting estimates in two-way tables by incorporating outside information. Canadian Journal of Forest Research. 18: 1280-1285.

Scott, C.T. 1979. Midcycle updating: some practical suggestions. In: Forest resource inventories, Vol. I; 1979 July 23-26; Ft. Collins, CO. Ft. Collins, CO: Colorado State University: 362-370.

Scott, C.T. 1984. A new look at sampling with partial replacement. Forest Science. 30(1): 157-166.

Scott, C.T. 1986. An evaluation of sampling with partial replacement. In: Use of auxiliary information in natural resource inventories; 1985 Oct. 1-2; Blacksburg, VA. Society of American Foresters SAF 86-01: 74-79.

Scott, C.T.; Köhl, M. 1994. Sampling with partial replacement and stratification. Forest Science. 40(1): 30-46.

Stott, C.B. 1947. Permanent growth and mortality plots in half the time. Journal of Forestry. 45: 669-673.

Theil, H. 1971. Principles of econometrics. New York: John Wiley & Sons. 736 p.

Van Deusen, P.C. 1989. Multiple-occasion partial replacement sampling for growth components. Forest Science. 35(2): 388-400.

Van Deusen, P.C. 1996. Incorporating predictions into an annual forest inventory. Canadian Journal of Forest Research. 26(10): 1709-1713.

Ware, K.D.; Cunia, T. 1962. Continuous forest inventory with partial replacement of samples. Forest Science Monograph. 3. 40 p.

An Analysis of Mortality Inventory Tally Using Large Plots Compared to Tally Using Small Plot Clusters

Vernon J. LaBau and John W. Hazard

Abstract.—During an inventory to assess spruce bark beetle impact on the Kenai Peninsula in south-central Alaska, 5-year mortality estimates were made for all growing-stock trees on 0.6 ha areas, on 0.4 ha areas, and on a cluster of four 1/60-ha subplots. The analysis of the results of the comparison between cluster data and the larger plot data highlighted some of the problems associated with trying to assess tree mortality from small plots. Based on the large chi square values observed in these tests, there seems to be a strong case for taking a mortality plot that is larger than the four 1/60-ha plots tested here. For the population under study, the smaller plots do not capture the highly variable distribution nature of mortality as well as the two larger plots evaluated.

BACKGROUND

During the summer of 1997 and 1998, the University of Alaska-Anchorage (UAA), through the Environment and Natural Resources Institute (ENRI), funded a study to evaluate the spruce bark beetle (*Dendroctonus rufipennis* (Kirby)) impact on the forests of the Kenai Peninsula in south-central Alaska (LaBau, in press). As a result of the forest stands reaching old age, the spruce bark beetle is the force behind one of the largest current and ongoing insect epidemics in the United States. It impacted over 1.3 million acres of Alaska white spruce (*Picea glauca* (Moench) Voss) and Lutz spruce (*Picea* x lutzii Little) during the spring and summer of 1996 (Boughton 1996).

OBJECTIVES

One of the objectives of this study was to evaluate how well the four-point cluster of subplots captured the highly variable nature of the mortality population of interest. It was felt that some measure of that could be obtained by comparing the four-point cluster mortality data set with the data set found on the .6-ha sample. The .6-ha plot completely encompasses the four-point cluster, so it is possible to compare these two samples. A second point of focus for the study was to evaluate how well the four-point plot evaluated for mortality compared to the .4-ha plot, and how well the .4-ha plot evaluated mortality compared to the .6-ha plot.

The null hypothesis was that for each of the four strata under test: "*there is no significant difference between the **Expected** tally of mortality trees on the .6-ha sample and that of the **Observed** tally of mortality trees on the four-point cluster sample.*" It was decided that the occurrence of a chi square value larger than that at the 0.05 level would be considered sufficient to reject the null hypothesis. The tests were made for each of four mortality intensity strata, with each stratum having 10 plots, resulting in a total of 40 data sets over the four impact strata, and resulting in 10 degrees of freedom in the test for each stratum.

METHODS

Employing a two-phase (double) sampling methodology for stratification (Bickford 1952), ENRI evaluated 1,078 photo sample points at the first (photo interpretation) phase and established 40 phase 2 ground plots in four strata classes as identified in phase 1. The strata in this study were based on spruce bark beetle attack intensities as derived from annual aerial insect damage survey maps prepared by the USDA Forest Service's office of State and Private Forestry (S&PF) (Holsten *et al.* 1996) in cooperation with the State of Alaska's Division of Forestry, (Alaska Department of Natural Resources 1995). The four strata used in this study were "High," "Moderate," "Low," and "None," indicating the level of bark beetle attack in the immediate vicinity of the photo sample points. A study plan is available describing in greater detail how the strata were classified during phase 1 of the sample process.

Data were collected on the ground plots, using standard forest inventory methodologies (Larson 1987) and standard forest health evaluations (Conklin 1996) as set forth by the Forest Service in its Forest Inventory and Analysis (FIA) and Forest Health Monitoring (FHM) programs.

The standard FHM ground sample unit is four 1/60-ha subplots, resulting in a sample of 1/15-ha at each ground plot cluster for growing-stock trees (see figure 1). Data

---

Senior Research Associate, University of Alaska, Anchorage, AK, USA, Environment and Natural Resources Institute, and Partner, Statistical Consulting Services, Bend, OR, USA, respectively.

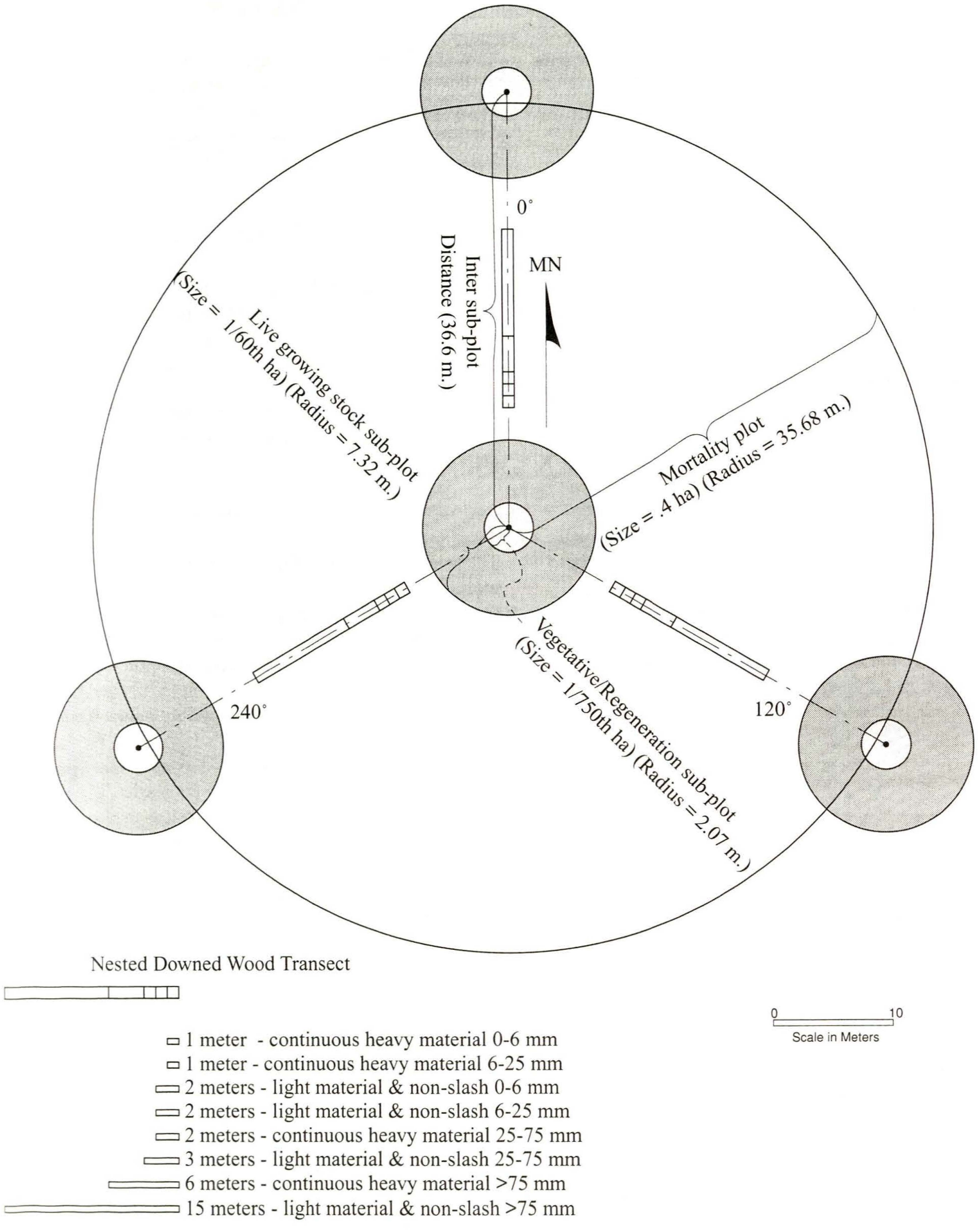

0°
MN
Inter sub-plot Distance (36.6 m.)
Live growing stock sub-plot (Size = 1/60th ha) (Radius = 7.32 m.)
Mortality plot (Size = .4 ha) (Radius = 35.68 m.)
Vegetative/Regeneration sub-plot (Size = 1/750th ha) (Radius = 2.07 m.)
240°
120°
Nested Downed Wood Transect
1 meter - continuous heavy material 0-6 mm
1 meter - continuous heavy material 6-25 mm
2 meters - light material & non-slash 0-6 mm
2 meters - light material & non-slash 6-25 mm
2 meters - continuous heavy material 25-75 mm
3 meters - light material & non-slash 25-75 mm
6 meters - continuous heavy material >75 mm
15 meters - light material & non-slash >75 mm
0
10
Scale in Meters

Figure 1.—*Standard FHM ground plot layout with the addition of the 0.4 ha mortality plot used in this study.*

were collected on growing stock, seedling and sapling regeneration, and understory vegetation at each subplot. Normally, FIA and FHM collect mortality tree data on those same clusters of subplots. This was also done in this study. However, in this study, an additional 0.6-ha mortality plot was laid over the cluster of subplots, and all growing-stock trees (all trees 12.7 cm and larger) that died within the last 5 years (guides in FIA procedures (Larson 1987)) were selected in the growing-stock mortality sample.

DATA ANALYSIS

During the course of the ground sample, more than 1,700, 1,100, and 200 mortality growing-stock trees were tallied respectively on the 40 0.6-ha plots, the 0.4-ha plots, and on the same 40 clustered subplots sets. Because the subplot clusters were only 1/9 the size of the 0.6-ha plot, the sample of mortality trees from the clusters were expanded accordingly to enable a valid comparison of tree tally on an area-by-area and tree per hectare basis. Table 1 summarizes the tree tallies by species for the 0.6-ha, 0.4-ha, and four-point cluster samples, with all scaled to a per acre basis for valid comparisons in the analysis.

The method chosen for comparing these data sets was the chi square analysis test of accuracy (Freese 1960), where the mortality tally on the 0.6-ha plot would be the *Expected* count and the mortality tally on the four subplots or the 0.4-ha plots would be the *Observed* count. Tests would be made for each of the four strata, since each stratum had different intensities of mortality tally.

Then:

$$X^2=\sum_{i=1}^{10}\left(\frac{(x_i-\mu_i)^2}{\sigma^2}\right).$$

where: χ_i = the ***observed*** value from the ith cluster sample, or the 0.4-ha plots,

μ_i = the ***expected*** value from the ith 0.6-ha sample, and

σ^2 = the required accuracy, which for this case is defined as

$$=\frac{(10\%\text{ deviation from the average strata mortality tally})^2}{(\text{The standard normal deviation for a 0.05 two-tailed test})^2}$$

and for the "High" strata with an average tally of 52.1 trees per acre on the 0.6-ha sample is:

$$= \frac{(5.21)^2}{(1.96)^2} = 7.066 \text{ trees}$$

The required accuracy for the "Moderate," "Low," and "None" strata were 2.17, 2.11, and 0.06 trees, respectively.

RESULTS

Four chi square tests were run, one for each of the strata in the study; 10 pairs of data were tested in each stratum, providing 10 degrees of freedom for each stratum tested. For the 10 degrees of freedom in these tests, the chi square threshold for rejecting the null hypotheses at the 0.05 level is 18.31.

For all four of the strata evaluated, the null hypotheses were rejected at the 0.05 level, implying that the tally of mortality trees on the four-point cluster is significantly different from the tally on the 0.6-ha plot, and that neither the four-point cluster nor the 0.4-ha plot gives estimates of mortality as accurately as the 0.6-ha plot.

Results of the chi square evaluations for each stratum, as tested for the three combinations of plots, are shown in table 2.

DISCUSSION

The primary objective of this exercise focused on how the mortality tally on the four-point cluster and the 0.4-ha plot compared with the 0.6-ha plot. The 0.6-ha plot was used as our standard for comparison and provided the most information on mortality at each plot location. We were asking the question "Do the four-point cluster and the 0.4-ha plot provide estimates of the mortality on the 0.6-ha plots within an acceptable level of accuracy?". Freese's chi square test of accuracy was used to make this comparison. The Paired t-test and other comparisons of variance are not appropriate for this test, as explained in Freese (1960). Given the high chi square values observed in the test, it was concluded that the four-point cluster and 0.4-ha plot did not produce results within the acceptable level of accuracy.

Had it been established that the alternative methods (four-point cluster and 0.4-ha plot) reproduced the results of the standard method (0.6-ha plot), within the specified level of accuracy, then, it would have been appropriate to look at other characteristics, such as cost, convenience, quality control, and flexibility. However, this not being the case, these other characteristics were not evaluated.

Some additional comments need to be made about this study. First of all, results cannot be extended beyond the population tested, so it is not possible to extrapolate these results to all FHM plots in the United States, or the West Coast, or even to Alaska beyond the Kenai Peninsula. Second, the sample size (10 plots per stratum) is a smaller

Table 1.—*Summary of mortality tally for the three plot configurations under study, Kenai Peninsula, Alaska spruce bark beetle study, 1997 and 1998*

		Mortality tree tally				Trees per acre		
Beetle impact strata	**Plot**	**0.6 ha tally**	**0 .4 ha tally**	**4-point cluster tally**	**Plot**	**0.6 ha**	**0.4 ha**	**4-point cluster**
High	**7**	7	5	1	**7**	4.67	5	6
High	**52**	144	112	10	**52**	96.00	112	60
High	**63**	45	29	7	**63**	30.00	29	42
High	**75**	5	5	0.0	**75**	3.33	5	0.0
High	**82**	24	22	3	**82**	16.00	22	18
High	**89**	135	96	17	**89**	90.00	96	102
High	**92**	116	79	10	**92**	77.33	79	60
High	**111**	17	13	2	**111**	11.33	13	12
High	**124**	286	189	29	**124**	190.67	189	174
High	**129**	2	0.0	0.0	**129**	1.33	0.0	0.0
Low	**153**	42	22	13	**153**	28.00	22	78
Low	**160**	0.0	0.0	0.0	**160**	0.00	0.0	0.0
Low	**167**	4	2	2	**167**	2.67	2	12
Low	**176**	27	17	7	**176**	18.00	17	42
Low	**177**	11	11	3	**177**	7.33	11	18
Low	**188**	16	2	4	**188**	10.67	2	24
Low	**204**	152	101	18	**204**	101.33	101	108
Low	**214**	18	11	0.0	**214**	12.00	11	0.0
Low	**226**	61	37	1	**226**	40.67	37	6
Low	**248**	103	59	14	**248**	68.67	59	84
Moderate	**276**	0.0	0.0	0.0	**276**	0.00	0.0	0.0
Moderate	**283**	4	3	0.0	**283**	2.67	3	0.0
Moderate	**298**	49	35	5	**298**	32.67	35	30
Moderate	**313**	92	63	10	**313**	61.33	63	60
Moderate	**317**	0.0	0.0	0.0	**317**	0.00	0.0	0.0
Moderate	**337**	32	24	2	**337**	21.33	24	12
Moderate	**338**	1	1	0.0	**338**	0.67	1	0.0
Moderate	**343**	230	156	26	**343**	153.33	156	156
Moderate	**371**	12	12	1	**371**	8.00	12	6
Moderate	**374**	7	5	2	**374**	4.67	5	12
None	**386**	1	1	1	**386**	0.67	1	6
None	**389**	13	9	3	**389**	8.67	9	18
None	**407**	6	4	3	**407**	4.00	4	18
None	**409**	4	3	0.0	**409**	2.67	3	0.0
None	**414**	15	9	4	**414**	10.00	9	24
None	**417**	4	3	0.0	**417**	2.67	3	0.0
None	**428**	1	0.0	1	**428**	0.67	0.0	6
None	**438**	19	10	3	**438**	12.67	10	18
None	**448**	7	4	4	**448**	4.67	4	24
None	**461**	0.0	0.0	0.0	**461**	0.00	0.0	0.0
	TOTAL	1712	1154	206	**AVERAGE**	28.53	28.85	30.8:

Table 2.—*Summary of chi square computations for the three plot configurations under study, Kenai Peninsula, Alaska spruce bark bee 1997 and 1998*

								Chi Square test rejection value (0.05 level @ 10 df) =					
Impact strata	Plot	0.6 ha Mort/Ac. U	0.4 ha Mort/Ac. Z	4 points Mort/Ac. X	A 0.6x4pt X-U	B 0.6x.4 Z-U	C 0.4x4pt X-Z	A2 0.6x4pt	B2 0.6x.4	C2 0.4x4pt		Chi sqrs.	Accur toler (ta
high	7	4.7	5.0	6.0	1.3	0.3	1.0	1.8	0.1	1.0			
high	52	96.0	112.0	60.0	-36.0	16.0	-52.0	1,296.0	256.0	2,704.0	Acceptable U Miss (10%) =		
high	63	30.0	29.0	42.0	12.0	-1.0	13.0	144.0	1.0	169.0	Acceptable Z Miss (10%)=		
high	75	3.3	5.0	0.0	-3.3	1.7	-5.0	11.1	2.8	25.0	Chi Sq (.6x4pt.)=	309.1	
high	82	16.0	22.0	18.0	2.0	6.0	-4.0	4.0	36.0	16.0	Chi Sq (.6x.4)=	48.46	
high	89	90.0	96.0	102.0	12.0	6.0	6.0	144.0	36.0	36.0	Chi Sq (.4x4pt.)=	449.3	
high	92	77.3	79.0	60.0	-17.3	1.7	-19.0	300.4	2.8	361.0			
high	111	11.3	13.0	12.0	0.7	1.7	-1.0	0.4	2.8	1.0			
high	124	190.7	189.0	174.0	-16.7	-1.7	-15.0	277.8	2.8	225.0			
high	129	1.3	0.0	0.0	-1.3	-1.3	0.0	1.8	1.8	0.0			
	Totals	520.7	550.0	474.0	-46.7	29.3	-76.0	2,181.3	342.0	3,538.0			
	Means	52.1	55.0	47.4	-4.7	2.9	-7.6						
low	153	28.0	22.0	78.0	50.0	-6.0	56.0	2,500.0	36.0	3,136.0			
low	160	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Acceptable U Miss (10%) =		
low	167	2.7	2.0	12.0	9.3	-0.7	10.0	87.1	0.4	100.0	Acceptable Z Miss (10%)=		
low	176	18.0	17.0	42.0	24.0	-1.0	25.0	576.0	1.0	625.0	Chi Sq (.6x4pt.)=	2,331	
low	177	7.3	11.0	18.0	10.7	3.7	7.0	113.8	13.4	49.0	Chi Sq (.6x.4)=	107.4	
low	188	10.7	2.0	24.0	13.3	-8.7	22.0	177.8	75.1	484.0	Chi Sq (.4x4pt.)=	3,442	
low	204	101.3	101.0	108.0	6.7	-0.3	7.0	44.4	0.1	49.0			
low	214	12.0	11.0	0.0	-12.0	-1.0	-11.0	144.0	1.0	121.0			
low	226	40.7	37.0	6.0	-34.7	-3.7	-31.0	1,201.8	13.4	961.0			
low	248	68.7	59.0	84.0	15.3	-9.7	25.0	235.1	93.4	625.0			
	Totals	289.3	262.0	372.0	82.7	-27.3	110.0	5,080.0	234.0	6,150.0			
	Means	28.9	26.2	37.2	8.3	-2.7	11.0						
moder.	276	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
moder.	283	2.7	3.0	0.0	-2.7	0.3	-0.3	7.1	0.1	9.0	Acceptable U Miss (10%) =		
moder.	298	32.7	35.0	30.0	-2.7	2.3	-5.0	7.1	5.4	25.0	Acceptable Z Miss (10%)=		
moder.	313	61.3	63.0	60.0	-1.3	1.7	-3.0	1.8	2.8	9.0	Chi Sq (.6x4pt.)=	79.85	
moder.	317	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	Chi Sq (.6x.4)=	18.38	
moder.	337	21.3	24.0	12.0	-9.3	2.7	-12.0	87.1	7.1	144.0	Chi Sq (.4x4pt.)=	117.3	
moder.	338	0.7	1.0	0.0	-0.7	0.3	-1.0	0.4	0.1	1.0			
moder.	343	153.3	156.0	156.0	2.7	2.7	0.0	7.1	7.1	0.0			
moder.	371	8.0	12.0	6.0	-2.0	4.0	-6.0	4.0	16.0	36.0			
moder.	374	4.7	5.0	12.0	7.3	0.3	7.0	53.8	0.1	49.0			
	Totals	284.7	299.0	276.0	-8.7	14.3	-23.0	168.4	38.8	273.0			
	Means	28.5	29.9	27.6	-0.9	1.4	-2.3						
none	386	0.7	1.0	6.0	5.3	0.3	5.0	28.4	0.1	25.0			
none	389	8.7	9.0	18.0	9.3	0.3	9.0	87.1	0.1	81.0	Acceptable U Miss (10%) =		
none	407	4.0	4.0	18.0	14.0	0.0	14.0	196.0	0.0	196.0	Acceptable Z Miss (10%)=		
none	409	2.7	3.0	0.0	-2.7	0.3	-3.0	7.1	0.1	9.0	Chi Sq (.6x4pt.)=	16,801	
none	414	10.0	9.0	24.0	14.0	-1.0	15.0	196.0	1.0	225.0	Chi Sq (.6x.4)=	166.6	
none	417	2.7	3.0	0.0	-2.7	0.3	-3.0	7.1	0.1	9.0	Chi Sq (.4x4pt.)=	21,712	
none	428	0.7	0.0	6.0	5.3	-0.7	6.0	28.4	0.4	36.0			
none	438	12.7	10.0	18.0	5.3	-2.7	8.0	28.4	7.1	64.0			
none	448	4.7	4.0	24.0	19.3	-0.7	20.0	373.8	0.4	400.0			
none	461	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0			
	Totals	46.7	43.0	114.0	67.3	-3.7	71.0	952.4	9.4	1,045.0			
	Means	4.7	4.3	11.4	6.7	-0.4	7.1						

sample than one would like to have to make statistical inferences from the study results. Given adequate funding, it would have been good to have been able to take at least four times as many plots (a minimum of 40 in each stratum). Third, the four-point cluster estimator should be unbiased, but from the results of this study, it seems that the smaller cluster plot size is not adequate for biologically describing what is on the ground, compared to the larger plots. A fourth point is that this test can be looked at as covering a spectrum of insect impact conditions ranging from endemic conditions (the "None" strata) to epidemic conditions (the "High" strata). This suggests that these results may have broader application to other similar conditions over the United States.

The four 1/60-ha cluster captures a very small sample of tree mortality, especially for endemic conditions. In view of the role of mortality as an indicator of forest health, it is very important to get the best possible data and information about what is causing trees to die. Mortality is not accurately assessed with the four-point cluster, thus making it difficult to find associations with stand characteristics (i.e., forest type, stand size, forest age, etc.), which are critical components for explaining forest health.

CONCLUSIONS

Based on the large chi square values observed in these tests, there seems to be a strong case for taking a mortality plot that is larger than the four 1/60-ha plots currently used by FHM. For the population under study, the smaller plots do not capture the highly variable nature of tree and plot mortality as well as the two larger plots evaluated.

ACKNOWLEDGMENTS

The following people reviewed this manuscript: Dr. Hans Schreuder, USDA Forest Service, Rocky Mountain Research Station, Ft. Collins, CO, USA, and Dr. Kim Iles, Kim Iles & Associates, Ltd., Nanaimo, BC, Canada.

We also would like to acknowledge the important contribution of Maynard Nuss, especially for his many hours as assistant to the principal investigator during data collection and editing.

LITERATURE CITED

Alaska Department of Natural Resources and USDA Forest Service. 1996. Alaska forest insect and disease surveys, 1995. Annual report prepared by Roger Burnside, Rebecca Zilliot, State of Alaska, Division of Forestry, and Kathleen Mathews, USDA, Forest Service, Region 10, State and Private Forestry. Anchorage, AK: Alaska Department of Natural Resources, Division of Forestry. 66 p.

Bickford, C.A. 1952. The sampling design used in the forest survey of the Northeast. Journal of Forestry. 50(4): 290-293.

Conklin, B. 1996. Forest health monitoring field methods guide. Research Triangle Park, NC: US EPA and USDA, Forest Service.

Freese, F. 1960. Testing accuracy. Forest Science. 6(2): 139-145.

Holsten, E.H.; Hennon, P.; Witter, D.; Matthews, K. 1996. Forest insect and disease conditions in Alaska—1995. Alaska Region. Gen. Tech. Rep. R10-TP-61. Washington, DC: U.S. Department of Agriculture. 40 p.

LaBau, V.J. 1999. Results of a pilot study to evaluate spruce bark beetle-induced tree mortality on the Kenai Peninsula, 1997. Anchorage, AK: University of Alaska, Anchorage, Environment and Natural Resources Institute. 25 p. In press.

Larson, F. 1987. Field procedures for the 1987 Kenai bark beetle inventory, Kenai Peninsula, Alaska. Field Manual. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Anchorage Forestry Sciences Laboratory. 112 p.

Some Aspects of Inventory Integration

Jerry Leech

Abstract.—Integrating such disparate topics as are covered by this conference is daunting, because to do it well requires in-depth expertise of many complex technical methodologies. Based on experiences in Asia and Australia, it is suggested that there can never be one inventory design or one planning system. It will increasingly be necessary to implement specialized inventories and projects that are oriented towards meeting specific short-term and longer term objectives. Each separate study must be designed to enable all the information to be integrated in order to answer the various alternative questions that will emerge in the future. Systematic sampling may often be preferred as the more pragmatic alternative to stratified random or multi stage, multi phase designs. Stratification will increasingly be carried out after plot measurement rather than before. It is often appropriate to build redundancy and flexibility into the project even at a significant cost. No one approach is correct for all circumstances, and any planner or inventory designer must understand all the disparate technologies in order to put together the most appropriate total package of linked systems.

This paper discusses some aspects of a strategy for collecting and integrating natural resource information based on practical experiences in intensive plantation management and extensive natural forest inventory and natural resource survey in various Asian countries and Australia. It is not intended as a single definitive statement but indicates that what is required is a flexible philosophy that can meet objectives as they change and emerge.

EVOLUTION OF INVENTORY DESIGN

Inventory field work is expensive. In the past this high cost has led to the implementation of stratified random sampling designs because these enable just enough samples to be measured in each stratum to achieve the design criterion. Incorporation of remote sensing and other spatial technologies for stratifying the forest led to multistage and multiphase designs that were optimized to achieve specific design criteria at minimum cost. Field work was replaced by calculation complexity. The generally adopted procedure was to design the inventory, then stratify the forest, and then establish the field plots.

Although this is obviously the ideal approach, my experience has been that such designs are not appropriate in developing countries where the objectives of the inventories are often not so clearly defined; even if the objectives are well defined at the time of the inventory design, they have a habit of evolving over time into something quite different. What is needed is a flexible design that can meet changing objectives and changing needs. The design must also be allowed to develop as the skills of those working on the inventory develop and as their knowledge of the resource continually improves. This requirement for flexibility comes at an economic cost. However, without some flexibility, the risk that the inventory will not meet the changing objectives can be great.

In my opinion there are two practical difficulties with stratified random sampling and the more complicated multiphase multistage designs. Forest inventory is generally arranged in a manner that imposes a tight time schedule, and there is commonly not enough time to carry out the stratification before beginning the field work. Generally these two functions must be carried out in parallel even if this does increase the total cost. One example of this was the National Forest Inventory in Indonesia (Leech *et al.* 1996, Rombouts *et al.* 1996), a project that lasted approximately 7 years. The stratified random design proposed in the original documents was necessarily changed to a much higher systematic sample of field plots that could be established while the geographic information system (GIS) was being implemented in parallel. The stratification used for the preparation of the final statistics was available only during the last year of the project. The field work began in 1991, access was difficult in most areas, and species identification was also an almost intractable problem. At the end of the project, some 93 percent of the field plots had been measured, but only 91.5 percent were available for including in the final report. Stratified random sampling would have made it

---

Forestry Systems, P.O. Box 1632, Mount Gambier, S.A. 5290, Australia, Tel/Ans/Fax + 61 8 8725 6516, e-mail: jleech@dove.mtx.net.au.

impossible to complete the project within any reasonable time frame, but systematic sampling with post sampling stratification was feasible and effective, even though more expensive in terms of field work. It was a pragmatic rather than optimal solution.

The second difficulty that will become increasingly important in the future is that the use of GIS and various remote sensing and other technologies allow new stratifications to be developed almost at will. Certainly given the currently available technologies, any stratification developed before a 5-year program of plot measurement is likely to be largely irrelevant when the time comes to prepare inventory summaries. In the largest mangrove forest in the world, the Sundarbans Reserved Forest in Bangladesh, the systematic sample can now be used to determine which of various stratifications, such as alternative salinity stratifications, provides the most statistically efficient stratification. The plots can now be used to evaluate alternative stratifications that may be quite contradictory. This would not have been as simple if a more economically and statistically efficient stratified random sampling design had been implemented. What seems to me to be the best balance is to use a systematic grid and then to select points within that grid at random. Plot locations are then recorded by their nominal spatial location, but the actual location is also recorded as a plot attribute to facilitate stratification using the GIS.

The "simple" solution is to use differential global positioning systems (GPS) to locate the plots, but this is not always practical. For example, in Bhutan the steep terrain makes plot location and field work very difficult indeed. Real time differential GPS is not suitable if the field crews do not have access to computers and power for weeks on end. However, Garmin GPS units can locate plots to within about ±250 m, given the selective availability adjacent to China and given the lack of a suitable Digital Terrain Model (DTM). Recording the time and the satellites used to locate the plot location on a piece of paper would later enable more accurate spatial positioning using differential GPS. This means that both nominal and so-called actual plot locations need to be recorded and stored.

Systematic sample comes at a cost because more samples are required than for the more statistically robust and efficient stratified random and multistage and multiphase designs. However, the ease of calculation and the ability to modify the stratification after field sampling are so important in many situations that the economic costs would seem to be justifiable where flexibility is required. A further advantage is the ease in determining whether all the samples planned to be measured are in fact measured because incomplete sampling shows up readily on a grid.

COMPLEX AND SIMPLE DESIGNS

Implementing a complex forest inventory design or research experimental design may save money, but forests change and the use of the information being collected may change, perhaps rendering a very complex and expensive project quite redundant.

One example in the intensively managed pine plantations in South Australia was a thinning/fertilizer interaction experiment. An economic analysis had shown that a very important economic advantage might be gained by modifying the thinning regime considered optimal economically if post-thinning fertilizer was applied. There was believed to be an interaction between the thinning and fertilizer application, and a complex and costly experiment was justified. In the large trial (O'Hehir *et al.* 1996), the accepted design for each site was 4 blocks by 12 fertilizer treatments by 3 levels of thinnings. The objective was 144 plots on each of four sites, each with 25 trees after the initial thinning. This requires a lot of field work, large areas of near uniform forest, and good mensuration and analysis to determine the effects. The initial results suggest that the interaction is not significant statistically but is significant economically. Analysis is continuing and is now the subject of a Ph.D. study. Originally one option—using simgle tree plots and more replicates—was considered to save space in the field and to reduce expense. This design would have been more complex to analyze because any extra growth would have changed the relative growing space, making it more difficult to develop the necessary model of the interactions although relatively easy to determine whether significant differences existed or not. In the end, the decision was made to use fewer replicates and 25-tree plots, the far more costly option.

Shortly after the first sites were established, the whole forest estate suffered an outbreak of Sirex (*Sirex noctilio*), and this ravaged some experimental sites, affecting some thinning treatments more than others. It has been possible, although somewhat difficult, to use the current plots to model the interaction. It would have been impossible to use the experiment if it had been designed as single-tree plots, because there would have been too few samples remaining after the Sirex attack.

Building this sort of flexibility into the original design may have been more expensive, but it was undoubtedly the best decision. Some apparent overkill is needed in the design every now and then.

INTEGRATING WOOD- AND NON-WOOD-BASED INVENTORIES

The GIS has been touted by some as providing the core reason for a paradigm shift in forest inventory design. If some spatial information cannot be effectively stored in a GIS, then it is not uncommon to hear the response "then why do you need it" as an excuse.

One of the best contrary examples I know is the Golpatta or Nipa Palm (*Nipa fruticans*) in the Sundarbans Reserved Forest in Bangladesh (Leech 1994, 1997). The Golpatta leaves are harvested annually and are vitally important for housing. There are some 40,000 to 80,000 ha of Golpatta in this forest, but all in discontinuous strips, generally no more than 5 m wide, along the banks of the khals or rivers. It is virtually impossible to map the Golpatta and therefore virtually impossible to use a GIS to store and manage the spatial information of this important resource. The most appropriate solution would appear to be to use the GIS to define broad ecosystem strata and then to use plots (measured spatially into forest, Golpatta, and water) to use the proportions of each land-use type to determine more accurately the area of Golpatta. The plot information also provides the necessary stocking information.

GIS technology is a very important and effective tool for forest inventory, but in some situations, it does not provide the complete solution to managing the spatial information.

LINKED STUDIES OR FULL INTEGRATION

Some years ago several organizations and authors proposed and implemented what were called totally integrated forest management planning systems. The primary advantage of this approach was that the use of one consistent planning approach for the development of forest management plans, making the planning holistic and generally very satisfactory.

The advantages of a fully integrated holistic system over the previous situation with many smaller separate systems are relatively obvious including better data integration; better systems integration; less costly field work because each visit to a plot obtained a wide range of information; good use of new technologies such as remote sensing; and minimal duplication of data, information, and effort. The advantages of having a totally integrated and holistic system were obvious. However, such systems have a few inherent disadvantages too that were not always fully understood. These systems are large and complex and therefore difficult to maintain, enhance, and eventually replace; they require a large commitment of manpower and resources; and they are less flexible when objectives and needs evolve over time. In the current general economic climate, large systems are often more difficult to finance.

A suggested alternative that makes sense in developing countries where objectives are often not clearly defined, and in many developed forests where information needs are continually changing, is to use a series of linked studies. Each separate project can therefore be justified and implemented separately, but it should be designed so that for a small overhead the information can be linked. This also has advantages in a country such as Bhutan where many forest management activities are funded by different donors, and it would be highly desirable to have one consistent coherent planning system for the whole country.

The objective then is to implement separate projects but to design them so as to facilitate integrated analysis. This requires commitment from the forest management authority to insist on the integration aspects, and it is acceptable only if the extra work involved has only a minimal impact on project feasibility.

INTEGRATION BETWEEN PROJECTS

The alternative to a large totally integrated system is to keep all projects completely separate, but this generally leads to the information not being able to be integrated at all. So complete integration appears generally unworkable economically, and completely separate independent projects generally lose information flexibility.

What appears to be needed is a linked series of studies, each of which could be justified, implemented, and analyzed separately and simply, but which would also be linked in ways that would facilitate analysis in a multidimensioned manner as well. The surveys do not have to be all be carried out by the one organization. In this way, the body of natural resource and ecological information about the forest area can be built up relatively simply. Basically four aspects to integration should be considered:

- integration between disciplines,
- spatial integration,
- integration over time, and,
- integration of data and information.

If one basic minimum core series of permanent sites is used as the basis for all studies in a complex ecosystem, this will assist integration between disciplines because a minimum set of consistent information can be collected by those people working in their different disciplines, and trend information will also become available. These sites can be augmented as any researcher deems desirable for a particular study, but a core set of permanent sites would be constant between quite different research projects. The integration must be both formal and informal with ongoing interaction between researchers.

In the Forest Resources Monitoring Project in China, the five disciplines (GIS, Remote Sensing, Field Inventory, Data Base, and Growth Models) were each led by specialist teams at four separate institutes (Beijing, Xi'an, Changsha, and Jinhua), although all teams were represented at each Institute. To succeed, the large project had to focus heavily on integration issues.

In one Bangladesh Integrated Management Project (de Vere Moss 1996), the challenge was to integrate specialists in zoology, botany, non-wood forest products, entomology, pathology, economics, silviculture, tourism, fisheries, and marketing, and to provide a sensible path for future development. This would have been a lot easier and more effective if the individual specialists had been instructed to use a core set of sites for each of their separate studies. Insisting on a minimum core set of sites for all disciplines would then allow future analysis across the information collected in each discipline and would facilitate analysis and integration of aspects that are not normally analyzed together. This enables different agencies or donors to fund different projects but still allow the information to be integrated.

Spatial integration is absolutely necessary. By ensuring that some sites are common between different projects, it will be possible to analyze quite disparate information sources and it may be possible to resolve quite important problems in this way.

Integration of information over time is essential for resolving many complex ecological and forest management questions. Various inventory projects in China, Myanmar, Indonesia, Bangladesh, and Bhutan have demonstrated to me how difficult it is to get time series trends, the trends that are essential if forest management planning is to be fully effective. A project-based approach with its necessary reliance on data collection at a single point in time is generally unable to provide this time series information necessary for good planning. Too often a new project changes the inventory design for some sound reason but at the cost of reducing the ability to get trend information. In one country, it was suggested by a consultant that the method of locating the grid plot centers should be changed from latitude and longitude to UTM (Universal Transverse Mercator) because this will ensure that each sample represents an equal land area. The gain is minimal compared with the loss of potential growth information in the short term.

It is highly desirable that all information, including information collected by different organizations, be integrated into the one set of database structures. The same idea of loosely integrated studies can be carried forward into integrating the information. One method is to insist on a minimum data dictionary for database fields and to insist on using one relatively simple but readily available database package. The various dBase-based database packages provide one way of achieving this. Most other high level programming languages can access dBase-structured files, so the overhead imposed through insisting on one database style is not exorbitant. This is obviously not the technically most competent computing solution for any of the separate analyses, and it does not look like a neat solution. However, the approach is pragmatic because it will minimize the cost overhead for individual projects and will enable the disparate databases to be linked.

ASPECTS OF INTEGRATING FOREST INVENTORY AND NATURAL RESOURCE SURVEYS

The Forest Resources Management Project (FRMP) in Bangladesh carried out a detailed forest inventory in the forest divisions to develop management plans for the production forest. The primary objective was to estimate standing volume of trees. Independently, a Natural Resources Survey (NRS) was conducted in the protected areas to survey vascular plants and vertebrate animals; the primary objective was to prepare species lists and to form some guidelines for developing prescriptions for conservation management. Integrating the information from these two surveys was difficult because the area bases are different, the objectives were different, and the data collected were also different. What was needed by the project was an integrated management plan that effectively integrated these two information sources.

An Extended Natural Resources Survey (ENRS) was designed and implemented very satisfactorily by the Forest Department in Bangladesh and reported by Leech and Ali (1997b). Table 1 summarizes the essential features of the three surveys. It can readily be seen that the ENRS provides information linkages to both the forest inventory and the NRS and enables comparisons to be made. Without the ENRS, it would have been impossible to effectively prepare an integrated management plan because there were no information linkages between the Natural Resources Survey and the forest inventory.

THE SUNDRI DIEBACK PROBLEM IN THE SUNDARBANS OF BANGLADESH

The Sundarbans Reserved Forest in Bangladesh is the largest contiguous mangrove forest in the world and covers over 400,000 ha of land. The main tree species are Sundri (*Heritiera fomes*) and Gewa (*Excoecaria agallocha*). The ecosystem is obviously very fragile but it is vitally important to the psyche of Bangladesh because it is the home of an estimated 300-450 tigers (*Panthera tigris*). Some 2.5 million people live with 10 km of the SRF and the socioeconomic pressure is great. The Sundri is interesting in that within a very short distance you can see Sundri trees with young leaves, old leaves, and trees suffering a mysterious dieback with thin crowns and dying leaves. I have not yet seen an effective use of remote sensing in this situation; the reflectance differs

Table 1.—*FRMP: Forest Resources Management Project in Bangladesh*

NRS: **Natural Resource Survey**	**ENRS:** **Extended Natural Resource Survey**	**Forest Inventory**
• 13 Protected Areas	• 8 FRMP Divisions 2 Candidate Protected Areas	• 8 FRMP Divisions
	• 11m circular plots 4 2x2m subplots	• 11m circular plots
• Gradsect (gradient directed transect) oriented across the habitat gradient	• 3 plots 100m apart oriented across the habitat gradient	• 5 plots 50 m apart in a fixed cross
• Arbitrarily selected sites to cover habitat gradient	• Randomly selected from systematic sample of inventory plots	• Systematic sample
• Not stratified	• Stratified	• Stratified
• Observations on gradsect and on the general area	• Observations on plots and on general area	• Observations on plots
• Objective was to maximize species counts	• Objectives are an unbiased estimate and species counts	• Objective was an unbiased estimate
• Vertebrate Animals Vascular Plants	• Vertebrate Animals Vascular Plants	• Trees and productive plants
	• Trees N, BA • Woody plants: N	• Trees: N, BA, Vol • Bamboo: N • Nipa: N
• Plants: Presence • Animals: Presence	• Other plants: Presence • Animals: Presence	
• Qualitative	• Qualitative • Quantitative	• Quantitative

without any change in vegetation and does not change when the vegetation observed on the ground does change, although there should be scope for submeter pixel resolution imagery to help interpret what is happening. Upstream in India is the Farakka Barrage, which has reduced the amount of water released through this large mangrove ecosystem.

Sundri dieback in the Sundarbans has been known to exist for many years. Different experts have suggested that the cause is salinity, changes in salinity, fungal pathogens, insect attacks, accretion, and sheet erosion. It would seem that all possible causes that appear to fit the distribution pattern are bedeviled by contrary examples. The problem of determining the cause or causes seems intractable, and there is insufficient expertise and little funding available to pursue the subject. In a joint paper with Mr. Syed Salamat Ali (1997a), we acknowledged that we do not have any answers but suggest that the best chance for determining the cause and then the most appropriate management strategy is to adopt a resource survey strategy that allows the separate specialists to conduct their own research programs but to insist that this is done in such a way that allows later integration of these disparate studies. This can be done by insisting on sampling at specific sites in addition to the sites selected by the researcher, and we suggest using 5-foot sites because these are compatible with the extensive forest inventory (1-foot sites of a cluster of five circular plots) and the Extended Natural Resource Survey (Leech and Ali 1997b) that used the subset of 5-foot sites. The Forest Department has a resources information management system, which is integrated with a geographic information system and can thus provide a way of integrating all the information on one facility and so assist any integrated analysis.

It would be impossible to design and implement one single experimental strategy aimed at resolving the issue; the many alternative hypotheses and possible causes make such a venture an exercise in futility. However, it is possible to implement separate specialized studies. What is needed are the linkages.

The existing knowledge led us to conclude that there appears to not be one single simple cause. Several different factors seem to combine to provide the circumstances that lead to Sundri dieback.

MEASUREMENT STANDARDS

If separate linked studies are to be effectively integrated, then the measurement standards used for any study must be appropriately defined, clearly stated, and well documented. This has generally not been well done in many past surveys. There is also a need for control enumeration to ensure that the collected data are reliable and precisely measured and that the measurement precision can be determined. Without this information about the precision of past surveys, it is difficult to effectively carry out analyses integrating disparate data sources when access to the people who carried out the earlier surveys has long since become unavailable.

SUMMARY

Not one single inventory design is appropriate for all circumstances. An inventory designer must consider the specific objectives that have been set and must understand the strengths and weaknesses of the various component technologies. Flexibility costs money, but experience suggests that this is money well spent.

ACKNOWLEDGMENTS

The thoughts expressed in this paper have developed over the years with the assistance of many professional colleagues. Some of these colleagues, and the formal referees (Dr. Kim Iles, Dr. David M.Hyink, and Dr. Cris Brack), have made valuable comments that have improved this paper. Their assistance is gratefully acknowledged.

LITERATURE CITED

de Vere Moss, P. 1996. Draft Integrated resource management plan of the Sundarbans Reserved Forest. UNDP/FAO Project BGD/84/056.

Leech, J.W. 1994. Interim report after the second mission as Mangrove Inventory Consultant. UNDP FAO Project BGD/84/056. Khulna, Bangladesh: Integrated Resource Development of the Sundarbans Reserved Forest. 46 p.

Leech, J.W. 1997. Integrating non-wood and wood inventories with new technologies. FAO Non-Wood News 4: 6-7.

Leech, J.; Ali, S.S. 1997a. Aspects of a general natural resources strategy for forestry in Bangladesh. 14 p.

Leech, J.; Ali, S.S. 1997b. Extended natural resources survey: Part III -Report. 157 p.

Leech, J.W.; Rombouts, J.; Yuyu, R. 1996. Report of the national forest inventory for Indonesia. UN FAO Project UTF/INS/066/INS, Field Document 58, Jakarta Indonesia. 149 p.

O'Hehir, J.F.; Boardman, R.; Leech, J.W. 1996. Mid rotation fertilizer and thinning: South Australian Project EP190 (results of preliminary analysis). Research Working Group No. 2: Mensuration and Management; 1996 November; Mount Gambier, SA. 18 p.

Rombouts, J.; Yuyu, R.; Leech, J.W. 1996. FFORS: The final forest resource statistics for Indonesia (excluding Java). UTF/INS/066/INS, Field Document 55, Jakarta, Indonesia. 146 p.

Towards a Plot Size for Canada's National Forest Inventory

Steen Magnussen, P. Boudewyn, and M. Gillis

Abstract.—A proposed national forest inventory for Canada is to report on the state and trends of resource attributes gathered mainly from aerial photos of sample plots located on a national grid. A pilot project in New Brunswick indicates it takes about 2,800 square 400-ha plots (10 percent inventoried) to achieve a relative standard error of 10 percent or less on 14 out of 17 estimates of forest strata (cover type) proportions; it takes about 3,300 plots of similar size to achieve the same precision target on 68 of 85 strata type x age proportions. Minimum cost solutions for fixed targets of relative precision and power include plot sizes from 71 to 192 ha and sampling intensities from 0.2 to 3.5 percent. Multivariate solutions exploiting the covariance in the data called for less sampling than univariate solution.

Plot size and number of sample plots are pivotal design parameters of any forest inventory. Procedures for optimizing these design parameters are well documented for single quantitative characteristics but less so for multilevel categorical variables such as forest strata (Rochon 1989). The effect of plot size on sample variances depends on the extent and spatial distribution of the sampled attribute, and is perhaps best described in terms of the spatial correlation function (Mahalanobis 1944) or the intraplot correlation δ. Briefly, the variance among plots equals the average within-plot covariance. The statistical efficiency of a plot size is governed by the decay rate of δ as plot size increases.

Canada is contemplating a new design for the national forest inventory. Data on area and extent of forest cover types (based on species composition and structure) are pivotal to the success of the inventory. Cover type data will come from interpretation of aerial photos (scale around 1:15000) of inventory plots located on a national grid. Photo interpretation is suited for the estimation of forest strata (Acka 1993) and can accommodate substantial sampling efforts in a cost-effective way. Ideally the photos would be taken and interpreted in a manner compatible to the reporting dates of the national inventory. Issues such as the size and number of plots needed to achieve a precision target on forest cover estimates have not been settled yet. To firm considerations, three pilot projects mimicking various design alternatives were established in New Brunswick, Ontario, and British Columbia to investigate the impact of plot size and number of plots on precision of estimates. In this study, we focus on the precision of estimates of areas of forest strata and strata x age classes (we henceforth use the more generic word strata in place of cover types).

MATERIAL AND METHODS

Data

Classified GIS polygons from the New Brunswick forest inventory (1981-1996) were used as data for this study. Delineation and classification of polygons were done from aerial photos (Leckie and Gillis 1995). Simulated sampling from this GIS coverage with 723 square plots of 6.25, 25, 100, 225, and 400 ha located on a square 10- x 10-km grid furnished the data. The 723 plot locations constitute all the 10- x 10-km nodes on the national forest inventory grid of sample locations in New Brunswick (7,265,912 ha). Figure 1 illustrates the grid and the GIS coverage extracted for each sample plot. Data for a single plot consist of the area and classification of each polygon inside the plot boundaries. The strata classes used in this study are listed in tables 1 and 2. All other classes were lumped into "others." Collectively we call the classes strata when no age distinction is made and we call them strata x age when an age group is associated with the class. The extracted data emulate, in part, the data types that would be generated during a national forest inventory.

Methods

Photo plots in the national inventory are the primary sampling units (PSU). Each PSU is considered an assembly of equally sized square secondary sampling units (SSU). The size of SSU was chosen as the minimum area that a photo interpreter would try to accommodate in the delineation of the photo plot into strata. Although the size of SSU is not explicit, we chose 0.01ha as the size of one SSU (Magnussen 1994). Note this 0.01-ha threshold is not to be confused with the minimum

---

Research Scientist, Research Officer, National Forest Inventory Manager, respectively, Department of Natural Resources Canada, 506 West Burnside Road, Victoria, BC, Canada V87 1M5.

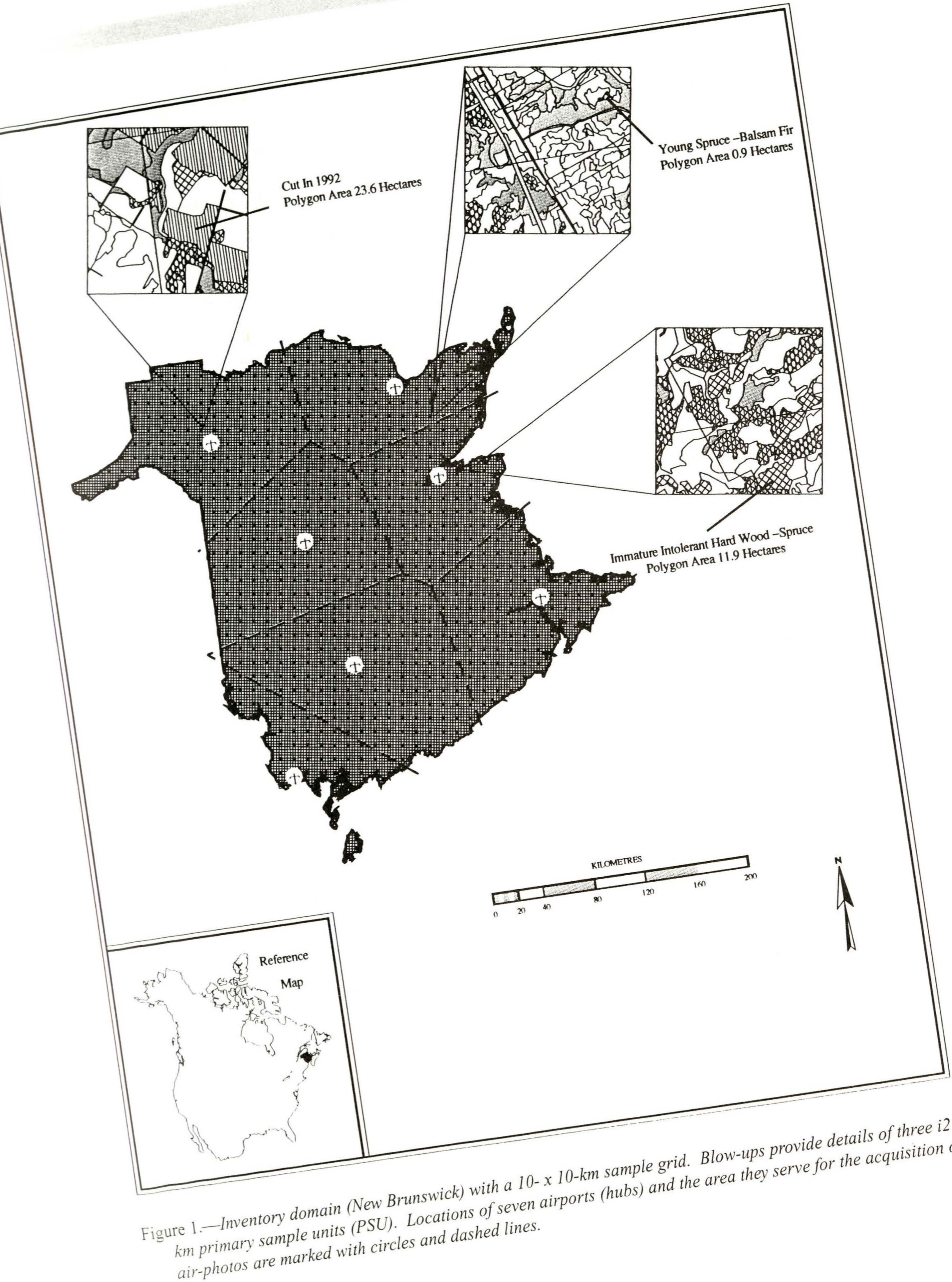

Cut In 1992
Polygon Area 23.6 Hectares
Young Spruce –Balsam Fir
Polygon Area 0.9 Hectares
Immature Intolerant Hard Wood –Spruce
Polygon Area 11.9 Hectares
KILOMETRES
0
20
40
80
120
160
200
N
Reference
Map

Figure 1.—*Inventory domain (New Brunswick) with a 10- x 10-km sample grid. Blow-ups provide details of three 2 x2 km primary sample units (PSU). Locations of seven airports (hubs) and the area they serve for the acquisition of air-photos are marked with circles and dashed lines.*

Table 1. *Sample estimates of strata proportions* $(\hat{p})$ *in New Brunswick, standard deviation of propensity of finding the strata in any given location* $(\hat{\sigma}_{prop.})$. *Results are based on interpretation of 723 plots of size 400 ha on a regular 10 x 10 km grid. Fit statistics of sample proportions to beta model* $(\hat{D}_{\max},\ P(\hat{D} \mid H_0))$ *describes the fit of the observed proportions to a beta distribution.*

Strata	$\hat{p}$	$\hat{\sigma}_{prop.}$	$\hat{D}_{\max}$	$P(\hat{D})$
Balsam Fir - Intolerant Hardwood	0.014	0.246	0.037	0.790
Balsam Fir - Spruce	0.060	0.269	0.068	0.290
Balsam Fir - Tolerant Hardwood	0.014	0.245	0.066	0.430
Intolerant Hardwood - Balsam Fir	0.018	0.247	0.061	0.440
Intolerant Hardwood - Spruce	0.032	0.251	0.072	0.300
Intolerant Hardwood - Tolerant Hardwood	0.020	0.249	0.062	0.440
Intolerant - Hardwood	0.046	0.259	0.058	0.350
Other - Softwood	0.028	0.250	0.066	0.310
Pine	0.010	0.246	0.026	0.800
Poor Site - Spruce	0.009	0.244	0.036	0.760
Spruce - Balsam Fir	0.163	0.304	0.052	0.180
Spruce - Intolerant Hardwood	0.023	0.247	0.090	0.300
Spruce - Tolerant Hardwood	0.033	0.251	0.099	0.240
Tolerant Hardwood - Balsam Fir	0.014	0.246	0.062	0.440
Tolerant Hardwood - Intolerant Hardwood	0.021	0.250	0.052	0.490
Tolerant Hardwood - Spruce	0.030	0.252	0.085	0.250
Tolerant - Hardwood	0.084	0.288	0.068	0.220

Table 2. *Sample estimates of age group proportions in New Brunswick, standard deviation of deviation of probability of finding an area of one of the five groups in any given location* $(\hat{\sigma}_{prop.})$. *Estimates are based on interpretation of 723 plots of size 400 ha on a regular 10 x 10 km grid. Fit statistics of sample proportions (area-weighted average across Strata x Age groups) describes fit of observed proportions to a beta model* $(\hat{D}_{\max},\ P(\hat{D} \mid H_0))$.

Age group	$\hat{p}$	$\hat{\sigma}_{prop.}$	$\hat{D}_{\max}$	$P(\hat{D})$
Regeneration	0.036	0.013	0.011	0.800
Immature-young	0.053	0.018	0.013	0.800
Immature-old	0.205	0.071	0.041	0.562
Mature	0.287	0.101	0.044	0.537
Old	0.039	0.014	0.015	0.799

area assigned to an individual forest stand. A SSU should contain only a single stratum (stratum x age) category. Larger SSU's will inevitably be mixed. Conceptually, an observation is made for each SSU in a PSU. In other words, we are dealing with a single-stage cluster design (Thompson 1992). All areas were rounded to nearest 0.01 ha before the analyses.

Estimation of strata proportions and their sample variances followed standard procedures for single-stage cluster sampling. The variance estimator of a forest type proportion (p) estimated from a sample of n_M primary units each with M SSU's taken from a finite number of N_M primary units of the same size is simply the variance of the primary sample unit corrected for the sampled fraction of the finite population. Another way of expressing this variance, and one that is better suited to explicate the impact of plot size, is (from Thompson 1992, page 122 after division by the square of the total size of New Brunswick , $N^2_M \cdot M^2$):

$$\hat{\sigma}_p^2(M) = \frac{(N_M - n_M)}{n_M \cdot N_M} \cdot \frac{(N_M \cdot M - 1)}{N_M - 1} \cdot \frac{\hat{\sigma}^2}{M^2} \cdot (1 + (M-1) \cdot \hat{\delta}_M) \qquad (1)$$

where $\hat{\sigma}^2$ is the estimated total population variance, $\hat{\delta}_M$ the average intraplot correlation in plots with M SSU's, and N_M is the number of primary units of size M in New Brunswick (a unit is counted as "in" if the majority of SSU's in the plot were part of the land base of New Brunswick). Estimation of δ_M is thus central to quantify the impact of plot size on sample variances. Equation 1 can be extended to the covariance between two strata (strata x age) in a straightforward manner.

The intraclass correlation within a plot arises because the joint probability of two separate SSU's having the same strata value deviates from their expected value. Formally, for a categorical class T occurring with probability p in the entire population (of SSU's), the average intraclass correlation in a plot with M SSU's (enumerated by U_1, $U_2, \ldots, U_M$, with U_i = {T, not T} for i=1,2,…,M) is :

$$\bar{\delta}_M = \underset{\forall i,j \in M \wedge j \neq i}{E}\left[\frac{\Pr(U_i = T, U_j = T) - p^2}{p(1-p)}\right] \qquad (2)$$

The joint probability for a single pair of SSU's will depend on the size of SSU's and the size of the plot. The average δ for a plot, however, depends only on the actual plot size. Equation 2 suggests a direct estimation of δ based on values assigned to the M SSU's in a PSU. Estimation of δ through analysis of variance (Landis and Koch 1977), estimation of a Dirichlet multinomial (Brier 1980), or estimation from the distribution of sampled proportions of strata areas (Prentice 1986) is possible.

We chose to estimate δ from the observed distributions of the 723 values of the proportion of a plot classified to a given stratum (stratum x age). Although not pursued further in this study, this approach is ideally suited for a hierarchical analysis of the effect of plot size (James 1975). When the probability of finding a given stratum (stratum x age) in an area of M SSU's follows a beta distribution with parameters α_M and β_M (the subscripts refer to the fact that the distribution depends on the number of SSU's in a plot), it can be shown that:

$$\delta_M = \frac{1}{(\alpha_M + \beta_M + 1)} \qquad (3)$$

Maximum likelihood estimates of α_M and β_M (Prentice 1986) were obtained for each stratum and all strata x age combinations from the observed proportions of a plot occupied by a stratum or strata x age. The cumulative distribution functions of the ensuing beta models were compared to the empirical distribution. A test of no difference was sustained [test: Kolmogorov-Smirnov, Conover paired with Holm's sequential rejection procedure] throughout (tables 1 and 2). When averaged across strata, the intraplot correlations were: 0.47, 0.29, 0.17, 0.12, and 0.11 for the 6.25-, 25-, 100-, 225-, and 400-ha plots, respectively. Relative standard errors, i.e., the standard error in percent of the estimated mean proportion, were 1.0, 0.9, 0.7, 0.3, and 0.3 percent. Corresponding correlations averaged across strata x age combinations were about 0.03 lower and with relative errors of 0.9 to 1.3 percent. In 11 strata x age categories, we failed to estimate the intraclass correlations for the 6.25-ha plot. Another 11 estimates failed to show a monotonic decrease with plot size. We excluded these 22 (of 85) cases from the analyses of trends in the strata x age results (4). A MANOVA approach to estimation of δ gave estimates of δ that were identical to within 0.002. Estimated cross-correlation $\delta_{i,j}$ between two strata (i,j, i≠j) were exploited for predicting all possible cross-correlation for any plot size M in the same way (4) as was done for the univariate correlation. Estimation of δ by way of estimating a Dirichlet multinomial (Brier 1980) produced frequency weighted results comparable (differences less than 0.01) to the mean intraclass correlations of strata or strata x age observations.

For each stratum and stratum x age, the δ for a plot with M SSU's was predicted from:

$$\hat{\delta}(M) = \tfrac{1}{2} - \frac{ArcTan[-(\hat{\lambda} + Log[M-1])/\hat{\omega}}{\pi} \qquad (4)$$

where λ and ω are regression parameters to be determined by nonlinear least squares (Gallant 1987). This model (a modified cumulative Cauchy distribution) was found suited for predicting the average correlation in plots to within 0.03 (90 percent confidence interval) whenever the spatial correlation (ρ) between two separate units of land centered at (x_i, y_i) and (x_j, y_j) is a power function of distance $\rho^{|x_i - x_j| + |y_i - y_j|}$. We surmise this to be the spatial correlation function behind the estimated average within plot correlation. At the strata level $\hat{\rho}$ was, on average, 0.968.

Total variance ($\hat{\sigma}^2$ in Eq 1) of a strata (strata x age) proportion was determined as the sum of within- (binomial) and between-plot (beta) variances. The estimate of the total variance obtained from the 723 plots of size M was:

$$\hat{\sigma}^2 = \frac{(M-1)\,\Gamma(\hat{\alpha}_M + 1)\,\Gamma(\hat{\beta}_M + 1)}{M\,\mathrm{B}(\hat{\alpha}_M, \hat{\beta}_M)\,\Gamma(\hat{\alpha}_M + \hat{\beta}_M + 2)} + \tag{5}$$

$$\frac{\hat{\alpha}_M \hat{\beta}_M}{(\hat{\alpha}_M + \hat{\beta}_M)^2 (\hat{\alpha}_M + \hat{\beta}_M + 1)}$$

where B is the complete beta integral. Each tested plot size gave rise to a separate estimate of the total variance. Provided that the beta distributions are internally consistent, we should not expect any difference in those estimates. However, the lack of fit may give rise to biased estimates. We tested the equality of the five estimates of total variance that were available from each strata and strata x age category with a Bartlett's test of variance homogeneity. The hypothesis was rejected 4 times (out of 17) at the strata level and 24 times (out of 85) at the strata x age level ($P < 0.01$). However, the marked kurtosis (median 25.5 for strata and 144.1 for strata x age) of the data inflated the rejection rate. A multivariate variant of the same test yielded a chi-square of 130.6 with 459 degrees of freedom ($P > 0.5$). Hence, we surmised that the total variance estimates derived from different plot sizes were indeed equal. Area-weighted averages were used henceforth.

From the estimates of total variance, predictions of δ for various plot sizes, and repeated use of equation (1), we computed the expected variance of strata (strata x age) proportions for a large number of designs by varying n_M, and M. Solutions were generated for a total 2,250 combinations of 150 plot sizes and 15 sample sizes. From these results, we then computed the number of plots and plot sizes that would satisfy 12 predetermined relative errors of precision through linear interpolations between available solutions. These calculations were completed in a univariate and a multivariate mode. Finally, we determined, for strata only, the number of plots (n) with M SSU's that would be needed to declare a relative error of x percent significant at the 100(1-0.05) percent level of significance with a probability of 90 percent (test power). Solutions were obtained by inversions from a multivariate F-test and a multivariate chi-square test. Assumptions about the distribution of estimated proportions were deemed satisfied for the entertained sample sizes (Fleiss 1981). For the chi-square test, the solution was the n satisfying (Rochon 1989):

$$F_{\chi^2_{\nu,\hat{\lambda}}}\left(q_{\chi^2_{\nu,1-\alpha}} \cdot \hat{C}\right) = 0.90 \tag{6}$$

where F is the cumulative distribution of the non-central chi-square distribution with ν degrees of freedom, non-centrality parameter λ, q is the $1-\alpha$ quantile of the central chi-square distribution with ν degrees of freedom, and $\hat{C}$ is equal to $1 + (M - 1) \bullet \hat{\delta}$. For strata analysis $\nu = 16$; α was fixed at 0.05; λ was estimated as the expected value of a chi-square statistic given the subsumed relative error on the estimated strata proportions. Specifically:

$$\hat{\lambda} = \Delta^2 \cdot \hat{\pi}_{strata} \cdot \tag{7}$$

$$\frac{n \cdot M}{(1 - \frac{n \cdot M}{NB}) \cdot (1 + M(1 - \hat{\delta}_{DM}(M))}$$

where Δ is the predefined subsumed error rate (fraction of estimated proportion), π_{strata} is the proportion of New Brunswick classified as one of the 17 strata (0.62), NB the number of SSU's in New Brunswick (determined by the majority rule), and M the number of SSU's in a plot of a given size (area); $\hat{\delta}_{DM}(M)$ is the predicted intraplot correlation for a plot with M SSU's derived from estimates based on the model in (4) fitted to values of Dirichlet multinomial intraplot correlations as defined by Brier. Solving the same problem but via a multivariate F-test with an observed F-value $\hat{F}$ (11) leads to n satisfying:

$$\Psi_{F_{\hat{\nu},\nu_2}}\left(\hat{k} \cdot q_{F_{\nu_1,\nu_2,1-\alpha}}\right) = 0.90 \tag{8}$$

where Ψ is the cumulative distribution function of an F distribution with ν and ν_2 degrees of freedom, k is a constant (9), and q_F is the $100(1-\alpha)$ percent quantile of an F distribution with ν_1 and ν_2 degrees of freedom. For strata-level solutions, $\nu_1=17$ and $\nu_2= n-(17-1)$. The parameters ν and k achieve an approximation of the non-central F-distribution with non-central parameter $\hat{F}$ to a central F-distribution. Direct computation of the probability values of the non-central F-distribution was prohibitive for the involved parameters. ν was estimated as:

$$\hat{\nu} = \frac{\left(\nu_1 + \hat{F}\right)^2}{\left(\nu_1 + 2\hat{F}\right)} \tag{9}$$

where $\hat{F}$ is the observed F-ratio (see 11).

$$\hat{k} = \frac{v_1 + \hat{F}}{\hat{F}} \qquad (10)$$

and finally,

$$\hat{F} = \vec{\Delta}' \cdot (\hat{\Sigma}_{tot}^{-1} \cdot \hat{\Sigma}_{\hat{\delta}}^{-1}) \cdot \vec{\Delta} \qquad (11)$$

where $\vec{\Delta}$ is the n_{strata} x 1 column vector of subsumed errors on the strata estimates (relative error times estimated proportion), and $\vec{\Delta}'$ denotes the transposed vector. $\hat{\Sigma}$ is the estimated covariance matrices with subscript *tot* referring to the total variance-covariances (estimated as per Landis and Koch and $\hat{\delta}$ to the predicted intraplot correlations and cross strata correlation predicted from models (4) fitted to estimated correlation (ibid.). Dropping the test-power simplified the above expression to finding an n that satisfied $\Psi_{\hat{F}_{v_1, n-(v_1-1)}} = 0.95$

A univariate approach to determine sample size via an F-ratio statistics followed the above procedure except that all covariance was set to zero.

Costs

Under the assumption that new photography and interpretation of photos is acquired for the purpose of the national forest inventory, we seek the inventory design (plot size, number of plots) with the lowest overall costs for a given predefined relative error of estimated proportions. The inventory costs include only design-dependent components: (i) flying to all plots in New Brunswick, (ii) photo acquisition (2 per plot) and processing, (iii) photo interpretation of plots consisting of a delineation of stand boundaries and classification into strata and age group, (iv) checking the photo interpretation by field visits, and (v) data processing. Table 3 lists the unit costs for each of these components. The total cost of a design was computed as the weighted sum where weights were either the number of plots or the area of a plot depending on the unit (table 3). Note while actual costs may vary considerably depending on local circumstances, we trust that their relative magnitudes have been captured. Relative values, not absolutes, determine the optimal design. Flying distances (FD, unit: km) to visit all national forest inventory plots in New Brunswick were predicted from the model on the next page (Eq. 12). The model was derived from measured total travel distance required to

Table 3. *Variable and fixed cost items for photo acquisition, photo-interpretation and field inspections.*

Item	Unit Cost ($)	Unit	Remarks
Flying	6.56	km	twin engine ($1000-$2200 per hour)
Interpretation	0.10	ha	strata delineation and age determination
Field visits	80.00	plot	site visits to one plot in 50 (2 people, one hour travel time to and from plot, $20/hr.) to check quality of interpretation
Field checks	0.12	ha	check interpretation (strata, age) by visual comparing interpretation results to field realities. 2 people can check 50 ha in 6 hours at $20/hour.
Fixed costs	20.00	plot	photos, plot registration, GIS work

visit all points on 40 different regular grids covering New Brunswick. The grids contained 100 to 5,000 plot locations. We assumed that the flying would be done from seven hubs serving as refueling stations (fig. 1). New Brunswick was, therefore, tiled into seven Voronoi cells, and travel distances for various grids were computed separately for each cell and then summed to a province-wide prediction model.

$$FD = Exp[5.94741 + 0.4787326 \cdot Log[n_M] + \frac{1}{2} \cdot 0.000176141] \qquad (12)$$

where the last term in the exponential is one half the residual variance of the regression. The range of the airplane was set to 1,400 km; excess flying includes travel to and from fuel stations. Initial travel distances to dispatch the airplane to the hubs are ignored. For example, the total travel distance for a design with 500 plots systematically allocated on a grid is predicted to be about 7,500 km and 10,500 km for one with 1,000 plots. An approximate formula is provided by FD ~ 335 x $\sqrt{n_M}$.

RESULTS AND DISCUSSION

Intraplot correlation for strata proportions declined at first rapidly and then more slowly as plot size increased (fig. 2

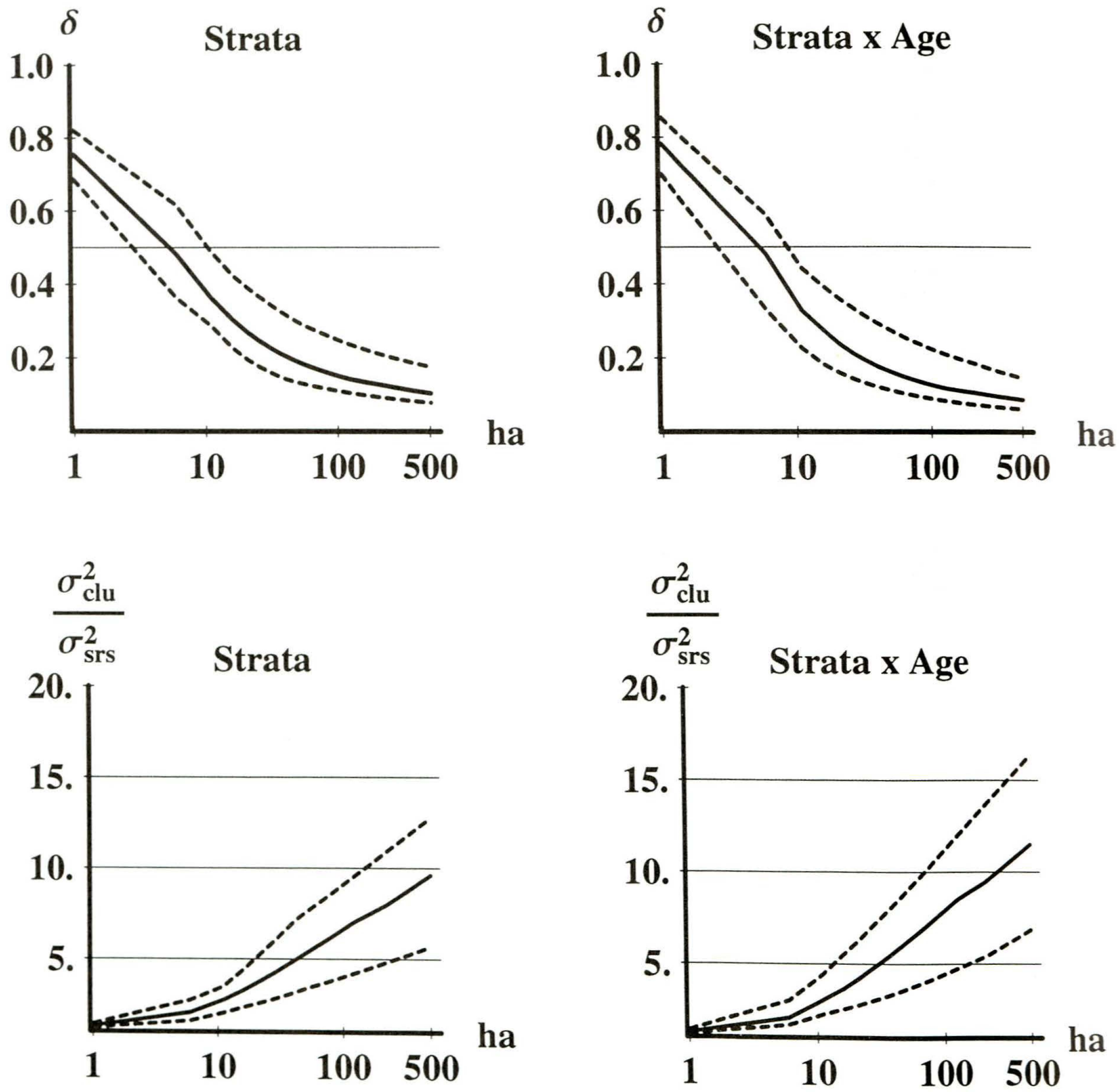


Figure 2.—*Top: Intraplot correlation (δ) versus plot size (ha). Full line: median. Dashed lines: upper and lower 10 percent quantiles. Bottom: Ratio of variance in cluster sampling* (σ^2_{clu}) *to the variance of simple random sampling* (σ^2_{srs}) *for various sizes (ha) of primary sampling units. Secondary sample unit = 100m².*

top, note the logarithmic x-axis). Increasing plot size from 100 m^2 to 10 ha, for example, caused a decline in average within plot correlation of 0.2, whereas an increase from 10 to 100 ha lowered the correlation by about 0.3, a pattern consistent with a spatial first-order autocorrelation process. Intraplot correlation varied among strata; figure 2 shows the 20 and 80 percent quantiles of the 17 strata and 63 strata x age combinations used in this study. Overall, an 80 percent confidence interval would be about 0.2 for smaller plots (< 10 ha) and shrink to about 0.1 for large plots (> 200 ha). Variance-weighted means for the five plot sizes were 0.46, 0.33, 0.21, 0.16, and 0.14, respectively. Simple means were 0.46, 0.29, 0.15, 0.13, and 0.11, while frequency-weighted estimates of δ for strata were 0.45, 0.29, 0.17, 0.13, and 0.11, respectively. For strata x age combinations, the decline was slightly steeper and the width of the 80 percent confidence band was somewhat wider, as dictated by their smaller proportions and higher degree of spatial scattering. Our choice of SSU (0.01 ha) has no effect on the above results; rather, a different SSU would merely impact on the resolution of results by virtue of the discreteness of SSU.

Intraplot correlation declined marginally at a rate below 1/M for a plot size increase from M to M+1, which means that the variance of a sample proportion based on a fixed sample area increased with sample size (fig. 2 bottom). Median sampling variances of strata proportions arising from sampling a fixed area with square 10-ha plots, for example, can be expected to be two times as high as sampling the same area with 100-m^2 plots. Conversely, 100- and 500-ha plots would inflate the variance sevenfold and tenfold. Results for individual strata varied greatly. Lower 10 percent bounds were roughly 0.5 the median value and the upper bound roughly 1.5 times the median. Going to the strata x age level (fig. 2 bottom) exaggerated parallel results by 10 to 50 percent.

The consequences of the tradeoff between plot size and number of plots are illustrated in figure 3. For a fixed inventoried area (x-axis), the expected precision drops exponentially as plot size goes up. For example, one could achieve a median error of 5 percent on a strata proportion by an inventory of about 1 percent of New Brunswick with square plots of 1 ha. Conversely, one would need to inventory about 4 percent of the province with a plot size of 25 ha to achieve the same precision. Insuring that most (80 percent) of the estimated strata proportions satisfy the target precision would add between 30,000 and 70,000 ha to the area inventoried. For a given inventory design, the median or 80 percent quantile precision at the strata x age is 1 to 5 percentage points lower than at the strata level. Finally, when inventory efforts to achieve a given precision with a fixed plot size are translated into necessary sample sizes, we get results as those in figure 4. We notice a dramatic increase in the minimum sample size needed to achieve, say a relative error of 10 percent, when plot size goes below 80 ha. For plot sizes in excess of 100 ha, the tradeoff between size and number of plots becomes more equitable. While relationships displayed in figures 2-4 are quite general, the actual numbers and their interrelationships are unique to the landscapes of New Brunswick.

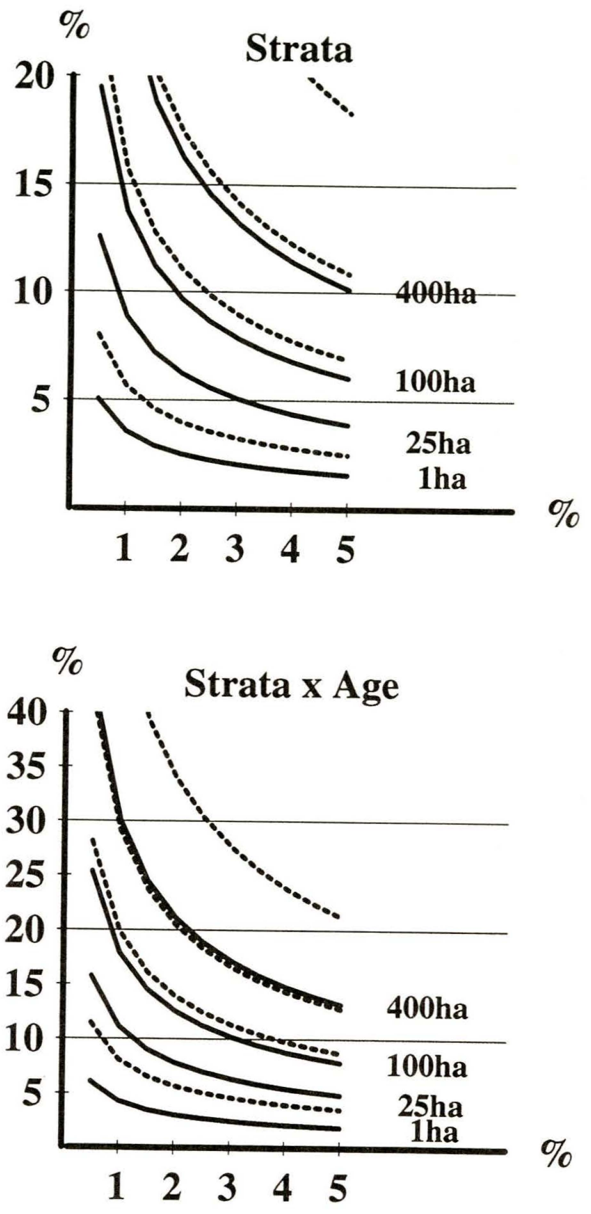


Figure 3.—*Expected relative error (%) of inventory estimates of strata and strata x age areas (y-axis) plotted against the percentage of New Brunswick inventoried (x-axis). Full lines: median result obtained with a plot size of 1, 25, 100, and 400 ha. Dashed lines are the corresponding 80% quantiles.*

As expected, costs for designs meeting a specified target precision varied considerably. Designs with plot sizes in the range of 70 to 130 ha for a target precision of 6 to 14 percent appear attractive (fig. 5). Smaller plots incur more flying costs but require less interpretation and data

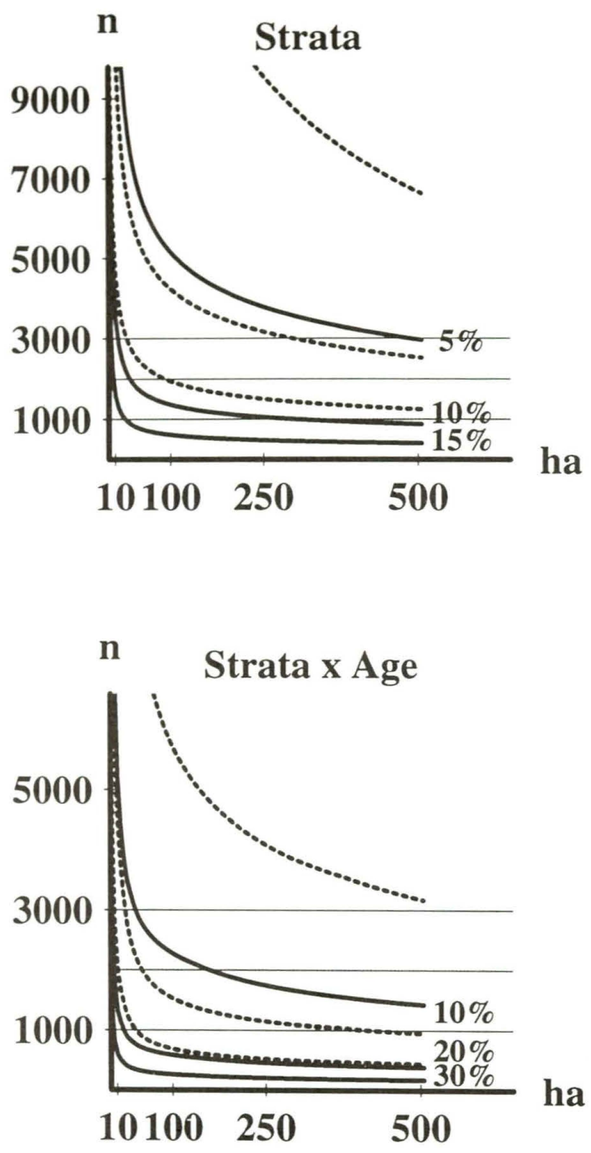


Figure 4.—*Number of plots (n) required to achieve a median relative error of 5, 10, and 15 percent on inventory estimates of strata and strata x age areas as a function of plot size (x-axis). Dashed lines are the combinations of plot size and number of plots needed to ensure that 80 percent of the results have errors less than 5, 10, and 15 percent.*

processing than larger plots. Table 4 lists the individual minimum cost solutions. The size of the most cost-effective plot increases when the target relative precision is lowered. Insuring that the target precision applies to 80 percent of the strata instead of just the 50 percent (table 4) appears to lower the plot size at the strata level, while the reverse is true at the strata x age level. The high number of plots needed to insure that 80 percent of the relative errors meet the target flipped the marginal cost relations between size and numbers of plots.

Precision targets can be further refined by imposing a threshold not to be exceeded with a probability of 100(1-α) percent and by requesting a minimum probability of detecting excess. These targets can be expressed as average expectations in a univariate or multivariate context. The latter exploits the covariance between inventoried attributes while the errors are averaged over all strata (strata x age). Estimates of total covariances were those from the MANOVA's, and predictions of cross-correlation were made via equation (4) adapted to a bivariate case. Table 5 presents five alternative minimum cost solutions, each based on a different set of probability statements or test statistics. In general, achieving a probability of 90 percent to declare an error in excess of the targets significant ($P \leq 0.05$) instead of one around 50 percent would entail an increase in the area inventoried of about 0.3 percent. In a multivariate context, the tradeoff between number of plots and size of plots is less clear than in a univariate framework due to the impact of covariance and the distribution of the test statistics. On average, a multivariate approach (Solutions I, II, and V) calls for less area to be inventoried than a univariate approach. The difference is most marked for low error targets and decreases with increasing error tolerance. Also, the choice of test statistics may modify the solution. For example, the II and V solutions in table 5 are accompanied by identical probabilistic statements and produce very similar solutions in terms of the total area to inventory, yet larger plots are clearly favored by solutions based on the F-test, a fact attributed to the trend for the determinant of the inverse of the covariance matrix to increase at a rate below 1/M when plot size is increased by one unit from M to M+1.

CONCLUSIONS

The tradeoff between the number of plots and the size of plots to use in a national forest inventory poses a classical dilemma for those who design the inventory. The quantitative analyses presented here cover only a narrow range of issues. Ultimately, it should be the value of the inventoried data that drives the design decisions about plot size and number of plots. For strata and strata x age area estimates, it is possible that the value may be inversely proportional to the estimate itself. In the context of conservation and biodiversity, focus will be on rare strata.

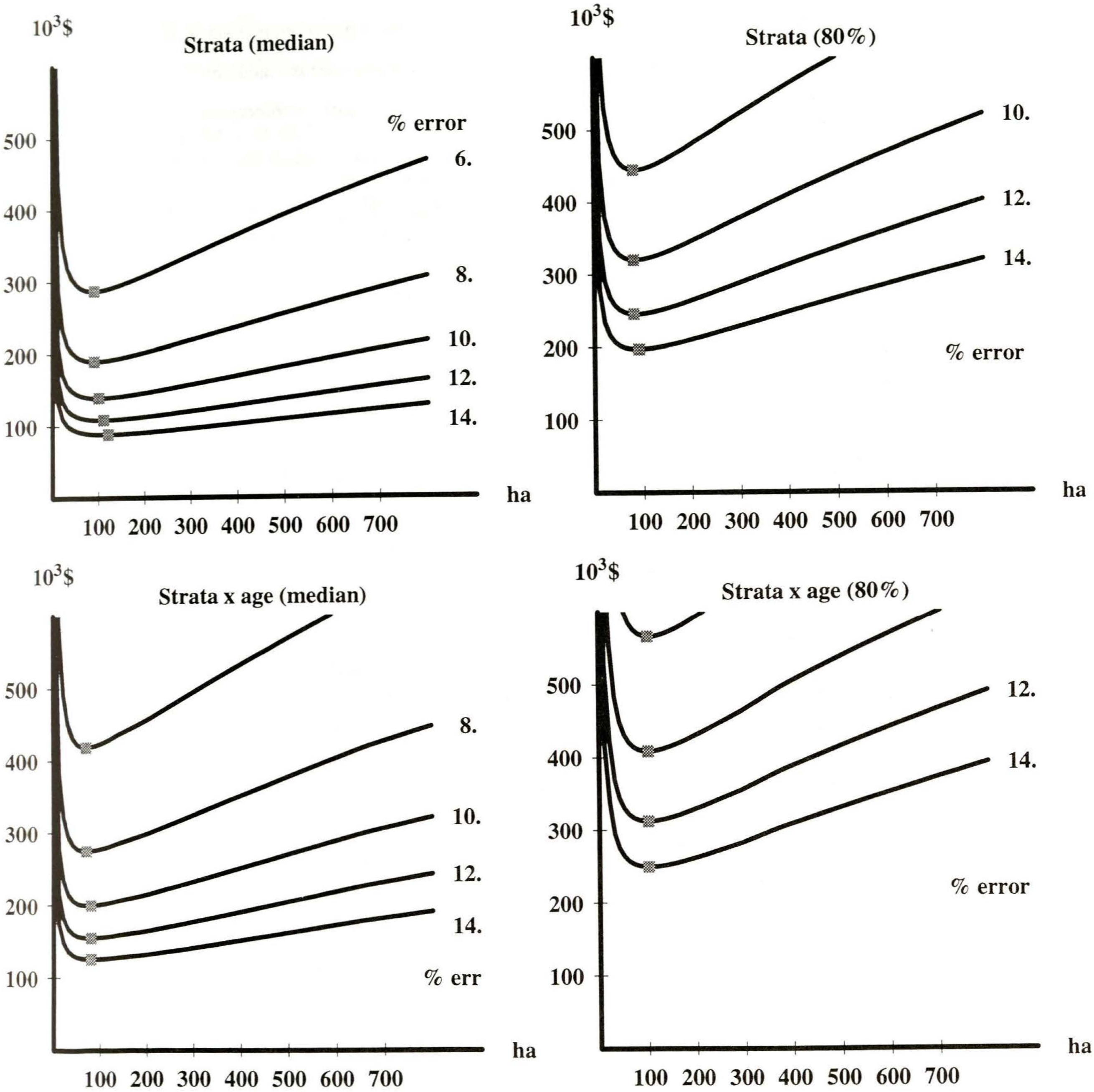


Figure 5.—*Effect of plot size (x-axis) on inventory costs (y-axis) when the number of plots is chosen to ascertain a target (median or the 80 percent quantile) relative error on the estimate of strata (strata x age) areas. The minimum cost solutions are indicated with gray squares.*

Sampling designs under the aegis of conservation and biodiversity issues are dictated by a very different set of imperatives than those epitomized by this study. Until the value of forest inventory information has been formulated, the best approach to settle the issue of plot size and number of plots is to minimize costs for a given precision target. Within this albeit narrow scope, a plot size in the order of 100 to 150 ha for stratifying the landbase by strata and age categories appears attractive when the precision targets fall in the 8 to 12 percent range. Note, however, that a precise formulation of these targets and the level (strata or strata x age) to which they apply can have a dramatic impact on the total area to inventory.

ACKNOWLEDGMENTS

We thank the New Brunswick Department of Natural Resources and Energy for making the GIS data available for our study. A special thank you goes to Director R. Dick, Forest Management Planning Section, for arranging

Table 4. *Lowest cost combinations of plot size and number of plots for a given relative error on estimated strata (strata x age) proportions. Error rates apply to either the median expectation or as an upper limit of 80% of the strata viz. strata x age combinations.*

	---------Relative error of estimate--------					
	6%	8%	10%	12%	14%	16%
Strata, Median						
Number of plots	3777	2169	1354	921	663	508
Spacing, approx., km	4	6	7	9	10	12
Size of plots, ha	91	91	101	111	121	121
π_{sample} %	3.9	3.6	1.9	1.5	1.2	1.0
Strata, 80%						
Number of plots	11062	6900	4542	3203	2291	1766
Spacing, approx., km	3	3	4	5	6	6
Size of plots, ha	91	81	81	81	91	91
π_{sample} %	9.3	6.1	4.4	3.3	2.7	2.3
Strata x age, Median						
Number of plots	6672	3863	2414	1690	1248	929
Spacing, approx., km	3	4	5	7	8	9
size of plots, ha	71	71	81	81	81	91
π_{sample} %	6.5	3.8	2.7	1.9	1.4	1.2
Strata x age, 80%						
Number of plots	12798	8550	5717	4069	3035	2270
Spacing, approx., km	2	3	4	4	5	6
Size of plots, ha	121	101	101	101	101	111
π_{sample} %	21.3	11.9	7.9	5.7	4.2	3.5

Table 5. ***Strata level multivariate F-test and Chi-square solutions to lowest cost combinations of plot size and number of plots for a given relative error on estimates.***

Solution I: Error is declared significant (P~ 0.5) at the $\alpha = 0.05$ level of significance of a type I error. Test: multivariate F-test.

Solution II: Error is declared significant (P=0.90) at the $\alpha = 0.05$ level of significance of a type I error. Test: multivariate F-test.

Solution III: Error is declared significant (P~ 0.5) at the $\alpha = 0.05$ level of significance of a type I error. Test: multivariate F-test with all covariances equal to zero.

Solution IV: Error is declared significant (P= 0.90) at the $\alpha = 0.05$ level of significance of a type I error. Test: multivariate F-test with all covariances equal to zero.

Solution V: Error is declared significant (P= 0.90) at the $\alpha = 0.05$ level of significance of a type I error. Test: Chi-square.

	---------Relative error of estimate--------------					
	6%	8%	10%	12%	14%	16%
Solution I						
Number of plots	915	589	394	297	200	193
Size of plots, ha	124	93	88	79	108	85
π_{sample} %	1.6	0.8	0.5	0.3	0.3	0.2
Solution II						
Number of plots	1101	616	395	277	215	160
Size of plots, ha	124	138	152	164	156	192
π_{sample} %	1.9	1.2	0.8	0.6	0.5	0.4
Solution III						
Number of plots	2055	1173	771	580	401	302
Size of plots, ha	105	108	108	113	115	129
π_{sample} %	3.0	1.7	1.1	0.9	0.6	0.5
Solution IV						
Number of plots	2494	1403	899	625	456	347
Size of plots, ha	103	111	117	123	136	147
π_{sample} %	3.5	2.1	1.4	1.1	0.9	0.7
Solution V						
Number of plots	2233	1248	791	539	387	299
Size of plots, ha	71	76	80	87	97	94
π_{sample} %	2.2	1.3	0.9	0.6	0.5	0.4

and facilitating data extraction and transfer, and to David Seemann for GIS support.

The following people reviewed this paper: Dr. J. Flewelling, Consultant Applied Statistics and Biometrics, Kent, WA, USA; Dr. S. Otukol, Ministry of Forest, Resource Inventory Branch, Victoria, BC, Canada; and Dr. M. Penner, Consultant, Huntsville, ON, Canada

LITERATURE CITED

Acka, A. 1993. Technique and importance of continuous forest inventory. Allgemeine Forst und Jagdzeitung. 164: 193-198.

Brier, S.S. 1980. Analysis of contingency tables under cluster sampling. Biometrika. 67: 591-596.

Gallant, A.R. 1987. Nonlinear statistics models. New York, NY: John Wiley and Sons.

Fleiss, J.L. 1981. Statistical methods for rates and proportions. 2d ed. New York, NY: John Wiley and Sons.

James, I.R. 1975. Multivariate distributions which have beta conditional distributions. Journal of the American Statistical Association. 70: 681-684.

Landis, J.R.; Koch, G.G. 1977. A one-way components of variance model for categorical data. Biometrics. 33: 671-679.

Levy, P.S.; Lemeshow, S. 1991. Sampling of populations: methods and applications. New York, NY: John Wiley and Sons.

Loetch, F.; Haller, K.E. 1964. Forest inventory. BLV. - Verlagsgesellschaft. Munich, GE.

Magnussen, S. 1989. Inter-plant interactions and their influence on within and among plot variances. Scandanavian Journal of Forest Research. 4: 369-377.

Magnussen, S. 1994. A coordinate-free area variance estimator for forest stands with a fuzzy outline. Forest Science. 42: 76-85.

Mahalanobis, P.C. 1944. On large-scale sample surveys. Journal of the Royal Statistical Society B. 231: 41-451.

Matérn, B. 1980. Spatial variation. Berlin, GE: Springer.

Okabe, A.; Boots, B.; Sugihara, K. 1992. Spatial tesselations concepts and applications of Voronoi diagrams. Chicester, UK: John Wiley and Sons.

Prentice, R.L. 1986. Binary regression using an extended beta-binomial distribution, with discussion of correlations induced by covariate measurement errors. Journal of American Statistical Association. 81: 321-327.

Rochon, J. 1989. The application of the GSK method to the determination of minimum sample sizes. Biometrics. 45: 193-205.

Thompson, S.K. 1992. Sampling. New York, NY: John Wiley and Sons.

Overview of the Forest Health Monitoring Program

Robert D. Mangold

Abstract.—This paper presents an overview of the Forest Health Monitoring Program (FHM), a partnership among the USDA Forest Service, State Foresters, universities, and the USDI Bureau of Land Management. The purpose of FHM is to annually assess the condition of the nation's forested ecosystems in a standardized way. There are four components of the program—Detection Monitoring, Evaluation Monitoring, Intensive Site Ecosystem Monitoring, and Research on Monitoring Techniques. At the current level of FHM development, approximately 60 percent of all forestlands in the lower 48 states, regardless of ownership, are covered by the Detection Monitoring permanent plot system.

Forests provide numerous benefits to society at large, including clean water, high-quality recreation, important habitat and biodiversity, wood products, and spiritual values. It is important for society to have a basic understanding of the condition of the forestlands of the United States so that critical policy decisions related to forest condition can be made.

The Forest Health Monitoring Program (FHM) started in 1990 as part of the Environmental Monitoring and Assessment Program (EMAP). This unique partnership among the USDA Forest Service (FS), the Environmental Protection Agency (EPA), State Forestry agencies, the Tennessee Valley Authority, the USDI Bureau of Land Management (BLM), the USDA Natural Resource Conservation Service, and numerous universities was established to respond to long-term forest health monitoring needs. Current partners include the FS, State Foresters, several universities, and the BLM.

The FHM program began in New England as a response to concerns about the effects of acid precipitation on local forests. Since then, it has expanded the permanent plot grid system to 27 states, covering 59 percent of the forestlands of the lower 48 states. The intent of the FS and State Foresters is to expand the plot system to all 50 states by 2003.

The overall purpose of FHM is to provide a basic understanding of conditions in our nation's forests by annually assessing the status and trends of forest ecosystem condition across all forestland ownerships. Data are collected and analyzed to determine the current condition and trends over time for a variety of forest ecosystem indicators. This information is used to guide management decisions.

CONCEPTUAL MODEL FOR FHM

Although there is not complete agreement in the forestry community on the definition of forest ecosystem health, there is a consensus emerging around the definition the FS uses, namely:

> Forest ecosystem health is a condition of forested ecosystems characterized at the landscape scale by ecological integrity and, within the capability of the ecosystems, sustainability of multiple benefits, products, and values.

There are two parts to this definition: one related to ecological integrity—defined as a concept that expresses the degree to which the biological and physical components (including structure, process, and composition) of an ecosystem and their relationships are present, functioning, and capable of self-renewal—and one related to human needs and values.

Sustainability is another term needing clarification. The World Commission on Environment and Development (1987) defined sustainable development as meeting the needs of present generations without sacrificing the needs of future generations. Sustainable forest management is viewed as the forest community's contribution to sustainable development and has been in the news extensively over the past few years (Mangold 1995). The FS and other forestry agencies are recasting their respective missions to meet sustainable forest management criteria.

In FHM we are viewing forest ecosystem health as an integral part of sustainability. The two concepts go hand-in-glove, with sustainability being the more encompassing term. However, it is clear that without healthy forests there can be no ecosystem sustainability. FHM attempts to measure indicators that are related to attributes of healthy ecosystems that Kolb *et al.* (1994) have expressed. These attributes include diversity of seral stages and stand

---

Acting National Program Manager, Forest Health Monitoring Program, USDA Forest Service, Washington, DC, USA.

structure for habitat, physical biotic and trophic network integrity, functional equilibrium between supply and demand of essential resources, and resistance to catastrophic change and ability to recover. Rapport *et al.* (1995) defined the attributes of a system judged to be in a non-sustainable condition—reduction in size of components, system retrogression, changes in species diversity, change in primary productivity, and change in nutrient cycling. Based upon the conceptual model for sustainability described above and extensive peer review, indicators of forest ecosystem condition were developed over time for FHM.

In 1995, the Santiago Declaration was signed by countries participating in the "Montreal Process" (Montreal Process 1995). This landmark voluntary agreement among 12 nations provided for the first time an internationally agreed upon system for characterizing sustainable forest ecosystems. It includes seven criteria that generally describe the components of sustainability, and within these seven are 67 measurable indicators. The criteria are biological diversity, productive capacity, ecosystem health and vitality, soil and water resources, global carbon cycles, socioeconomic factors, and legal-institutional factors. Twelve nations agreeing to characterize forests in a similar way and report on their progress to achieve sustainability based upon these 67 indicators was a historic event. The FHM program has cross-walked its program to link up with the Santiago Declaration so that we are measuring as many of these indicators as possible. For the 28 biophysical indicators, the FHM program, together with the FS Forest Inventory and Analysis program (FIA) is making a significant contribution to addressing 18 of them (table 1).

FHM STUCTURE

FHM has four interrelated phases. Together they provide a spatial and temporal sensitivity at national and regional scales for an integrated ecological assessment of forest health. All phases are needed. The first part is Detection Monitoring (DM), which has two components—the permanent plot grid system and the aerial and ground surveys. The permanent plot system is located on a national hexagonally based sampling grid, with fixed-area plots approximately 27 km apart. There are about 12,000 plots nationwide; about one-third of them occur in forests. Each plot is sampled on four fixed-area subplots that are each 7.32 m in radius. Details of the sampling design can be found in Smith *et al.* (1998). This grid provides the spatial sensitivity required to extrapolate results to a landscape level at national and regional scales. A series of indicators is measured on these plots every year in a nationally standardized way, so that the data can be aggregated from regional to national levels.

The other phase of Detection Monitoring is the annual aerial survey and other surveys conducted by the Forest Health Protection Staff within the State and Private Deputy Area of the FS. In essence, this phase of FHM can be viewed as the synoptic layer, i.e., it is nearly wall-to-wall coverage for forestlands in many states. This is an annual survey of about 85 percent of the nation's forests, done mostly from airplanes, in which areas of mortality, defoliation, and other conditions are "sketch mapped" onto topographical maps. The data are subsequently digitized and compiled in a standardized way and put into geographic information systems to provide annual maps of mortality and damage. The two systems—aerial survey sketch maps and the permanent plot grid system—are used together to identify either areas that need immediate treatment in the form of suppression of insect epidemics (like southern pine beetle identified in aerial sketch mapping) or areas that need further study because the permanent plot data indicate a troubling increase in crown dieback, for example.

Where further study is warranted, the second phase of the FHM program is initiated—Evaluation Monitoring. In this phase, a 2- to 3-year study of the trend observed either through aerial survey or the permanent plot grid is initiated to verify the extent of the problem and to ascertain the reason for the observed effect. This portion of the FHM program was begun in 1998 with the initiation of nine Evaluation Monitoring projects, some of which will be mentioned later in this paper.

The third phase of FHM is the Intensive Site Ecosystem Monitoring (ISEM). ISEM consists of a series of 21 intensive sites located in the major forested ecosystems of the United States. It provides critical information on time-sensitive indicators—i.e., some ecological effects will be entirely missed with only the once a year visit used in DM. ISEM will monitor at a higher temporal frequency, compared to Detection Monitoring, which will monitor at a spatially more intense frequency. Both phases are needed to provide accurate assessments and to ensure that no important effects are missed. Unfortunately, only incidental funding has been available to date to implement ISEM.

There are four main functions of the ISEM program:

1. ISEM sites will allow measurement of indicators that require monitoring over long periods of time. These indicators normally could not be measured during the usual 1-day site visit employed in Detection Monitoring. For instance, the timing of budbreak or budset requires personnel to be on site for several weeks at a time. Other components to be measured on ISEM sites include abiotic inputs, vegetation variables (structure, composition, regeneration, succession), soils, and aquatics and wetland variables.

Table 1.—*Ecological criteria and indicators for the sustainable management of forest ecosystems*

Santiago Declaration			
Criterion	**Indicator**	**Measurement**	**FHM and FIA Programs**
Biological Diversity			
Ecosystem diversity	Areal extent of forest types	Percent total forest	***
		Percent non-protected [a]	*
		Percent protected [a]	*
	Fragmentation of forest types		***
Species diversity	Forest-dependent species	Total number [b]	**P
		Status of risk species [c]	*
Genetic diversity	Proportion of former range		?
	Population levels of representative species [d]		*
Productive Capacity	Timber production [e]		***
	Total growing stock [f]	Plantations [g]	***
		Annual removal wood products [h]	*
Ecosystem Health and Vitality [i]	Insects and disease		***
	Competition from exotics		**P
	Abiotic stressors	Fire	***
		Storms	***
		Flooding	***
		Salination	***
	Management/use	Land clearance	***
		Domestic animals	*
	Air pollutants	S, N, O_3, etc.	**P
		UV-B	?
	Biological indicators of key Processes [j]	Epiphytes	***
		Insects	*
		Fauna	*
		Vegetation Communities	**P
Soil Resources [k]	Physical properties	Erosion	***
		Compaction	**
		Other physical properties	***
	Chemical properties	Organic matter	***
		Nutrients	***
		Toxins	**
	Protective functions [l]		**

(table continued on next page)

(Table 1 continued)

Criterion	Santiago Declaration Indicator	Measurement	FHM and FIA Programs
Water Resources [m]	Stream flow and timing		*
	Biological diversity		*
	Physical properties	Temperature	*
		Sediments	*
	Chemical properties	pH	*
		Dissolved oxygen	*
		Electrical conductivity	*
Global Carbon Cycles [n]	Total ecosystem biomass/carbon pool [o]		**
	Sequestration/release of carbon	Standing biomass	**
		Coarse woody debris	**P
		Peat	*
		Soils	***
	Forest products		*

*	=	Techniques for measurement or estimation developed in other programs
**	=	Techniques for measurement or estimation under development in FHM Program
**P	=	Techniques for measurement or estimation under development and tested in regional FHM pilot studies
***	=	Techniques for measurement or estimation developed by the FHM Program and implemented nationally
?	=	Unknown whether regional monitoring methods exist

[a] By forest types and age class.

[b] Number of forest-dependent species.

[c] Number of breeding populations.

[d] Species/diverse habitat/total range.

[e] Area and net area available; population estimate is coarser than those obtained by FIA.

[f] Merchant and non-merchant available.

[g] Area/growing stock, native and exotic species.

[h] Compared to sustainable volume.

[i] Based on area and percent forest affected.

[j] Nutrient cycling, reproduction, etc.

[k] Based on area and/or percent.

[l] Watersheds, floods, avalanche, riparian.

[m] Based on historical patterns.

[n] Contribution of forests.

[o] e.g., forest type, age class, etc.

2. ISEM will determine cause and effect relationships when Evaluation Monitoring projects do not provide clear resolution of an issue.

3. ISEM is also used to improve the current list of grid-based indicators used in Detection Monitoring. This is done through an intensification of the grid on ISEM sites and related research. We expect new indicators to be developed on ISEM sites as well.

4. ISEM sites will link continuous monitoring conditions, as measured on ISEM sites, with the anecdotal concerns of local managers about areas where no current data may exist. We should be able to correlate conditions observed on a regionally representative ISEM site with casually observed conditions in local management units. For example, we know some mushrooms fruit only every 10 years or so. If we know the flora associated with these kinds of mushrooms, we have a predictive indicator for other sites where we may need to manage for these mushrooms. This will be a very powerful tool, although the details need to be developed.

We have just begun to implement the ISEM portion of FHM. First projects have focused on linking the existing computer networks of Long-term Ecological Research areas (LTER's) that we expect to be included in FHM ISEM network so they have common and linked databases and common meteorological capability.

The fourth phase of FHM is Research on Monitoring Techniques (ROMT), which is our process of improving the existing indicators, data collection, analysis, and assessment reporting. It is an essential function and one that has contributed significant improvements to FHM, including a new statistical sampling design for the permanent plot grid system (the overlapping rotating panel design currently in use) and new indicator protocols for the vegetation structure indicator.

The four phases of FHM taken together are necessary to provide a powerful conceptual model for conducting integrated ecosystem monitoring. Integrated ecosystem monitoring is currently an important consideration in natural resource management. The National Environmental Monitoring Framework, a product of the Committee on Environment and Natural Resources (National Science and Technology Council of the White House), showed that to be effective, environmental monitoring needs to be done across scales (national to local), across agencies, and across media (terrestial, aquatic, air, etc.). This framework for monitoring across scales that uses intensive sites, systematic surveys, wall-to-wall surveys, and research is based on the FHM four-phase design (Committee on Environment and Natural Resources 1997).

INDICATORS MEASURED ON THE DETECTION MONITORING PERMANENT PLOT GRID SYSTEM

The cornerstone of FHM has been the visual crown rating measurements that are unique to FHM. We have devised a repeatable system to assess crown condition via several parameters—crown dieback (the amount of branches in the live crown that have died), foliage transparency (the amount of skylight visible through the live, normally foliated portion of the crown), and crown density (the amount of light blocked by branches, fruit, and foliage in a tree). We also record mensurational variables such as tree diameters, and heights on selected trees and we take species information. In addition, we measure a damage indicator that describes the type and amount of damage to the tree and its location on the roots, bole, or crown. The damage indicator does not ascribe causal agent because our program does not routinely use professional pathologists and entomologists to take plot data, and we feel the level of repeatability for ascribing causal agents is low for non-specialists. The aerial survey portion of Detection Monitoring provides us with the causal agent data that we need for immediate suppression treatments and other purposes.

We also monitor air quality impacts using two indicators. Damage from ozone is assessed using bioindicator plants that are sensitive to ozone. Lichen communities, key indicators of biodiversity and air pollution, are also measured. A full description of all measurement protocols can be found in the FHM Field Methods Guide (USDA Forest Service 1998).

A soils indicator is being fully implemented for the first time in 1998. This indicator is sampled by digging a small soil pit (no deeper than 50 cm) whereby the litter layer and the A horizon can be measured for depth and samples can be taken for lab analysis. Lab analysis includes assaying for total organic carbon and nitrogen in both the O and A horizons and assaying for exchangeable calcium, magnesium, and potassium in the A horizon.

We are also pilot testing several new key indicators in 1998 in five states. Vegetation structure is measured and consists of a full vascular plant inventory on three, 1-m square quadrats (plots) in each of the four fixed-area subplots. Within each square quadrat, vegetation is identified to the species level at four different levels of the forest canopy—at ground level (0 to 0.61 m), at 0.6 to 1.83 m, 1.83 to 4.88 m and greater than 4.88 m. This inventory gives us a good indication of biodiversity and wildlife habitat. From these data, we can also obtain the percent non-native (exotic) species present—currently a key interest. We also estimate the amount of coarse woody debris and the amount of fuel loading—which are key for quantifying rates of carbon sequestration and fire ecology and behavior—all are part of the Criteria and Indicators of the Montreal Process. If the pilot is successful in 1998 for these indicators, we expect to measure them in more states in 1999, or possibly nationally.

From the above list of indicators, it is clear that FHM is measuring a robust set of forest ecosystem health indicators. FHM has also considered implementing indicators for wildlife status. For example, we have developed a song bird indicator that has not yet been tested due to lack of funding. Other possible issues we are considering developing indicators for relate to amphibians or insect pollinators.

STATES INCLUDED IN THE PLOT SYSTEM

Currently there are 27 states within the Detection Monitoring plot system. They are Maine, New Hampshire, Vermont, Massachusetts, Connecticut, Rhode Island, Pennsylvannia, New Jersey, Delaware, Maryland, Virginia, West Virginia, Alabama, Georgia, North Carolina, South Carolina, Indiana, Illinois, Wisconsin, Michigan, Minnesota, Colorado, Idaho, Wyoming, California, Oregon, and Washington (fig. 1). Together these states make up about 59 percent of the forest lands of the lower 48 states—across all ownerships. The FS is commited to including all 50 states by 2003. However, all states have aerial and/or ground survey programs as part of the second component of Detection Monitoring, covering 85 percent of all forestlands in the United States.

FHM MANAGEMENT AND ORGANIZATION

FHM is organized into four "mega-regions"—North, South, Interior West, and West Coast (fig. 2). Each of the regions is managed by a regional manager; the overall program is managed by a national manager and two deputy national managers. FHM is a collaborative and consensus-driven program that is directed by an FHM Management Team. The Management Team consists of the national manager, four regional managers, two deputy national managers, representatives from the FS Regions and Northeastern Area Forest Health Protection staffs, four state representatives (from each of the FHM mega-regions), a representative from the National Association of

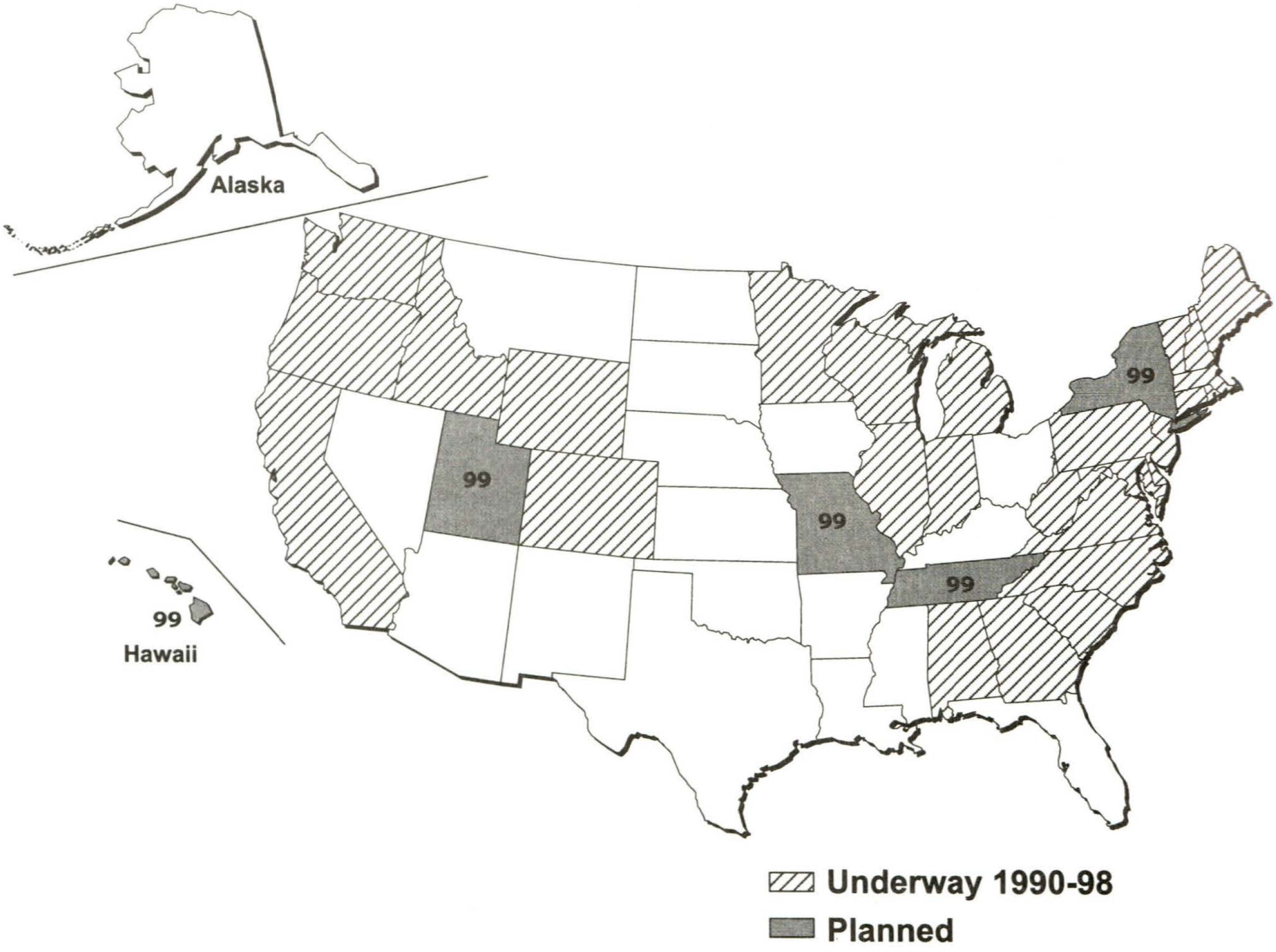


Figure 1.—*Implementation of detection monitoring plots for Forest Health Monitoring.*

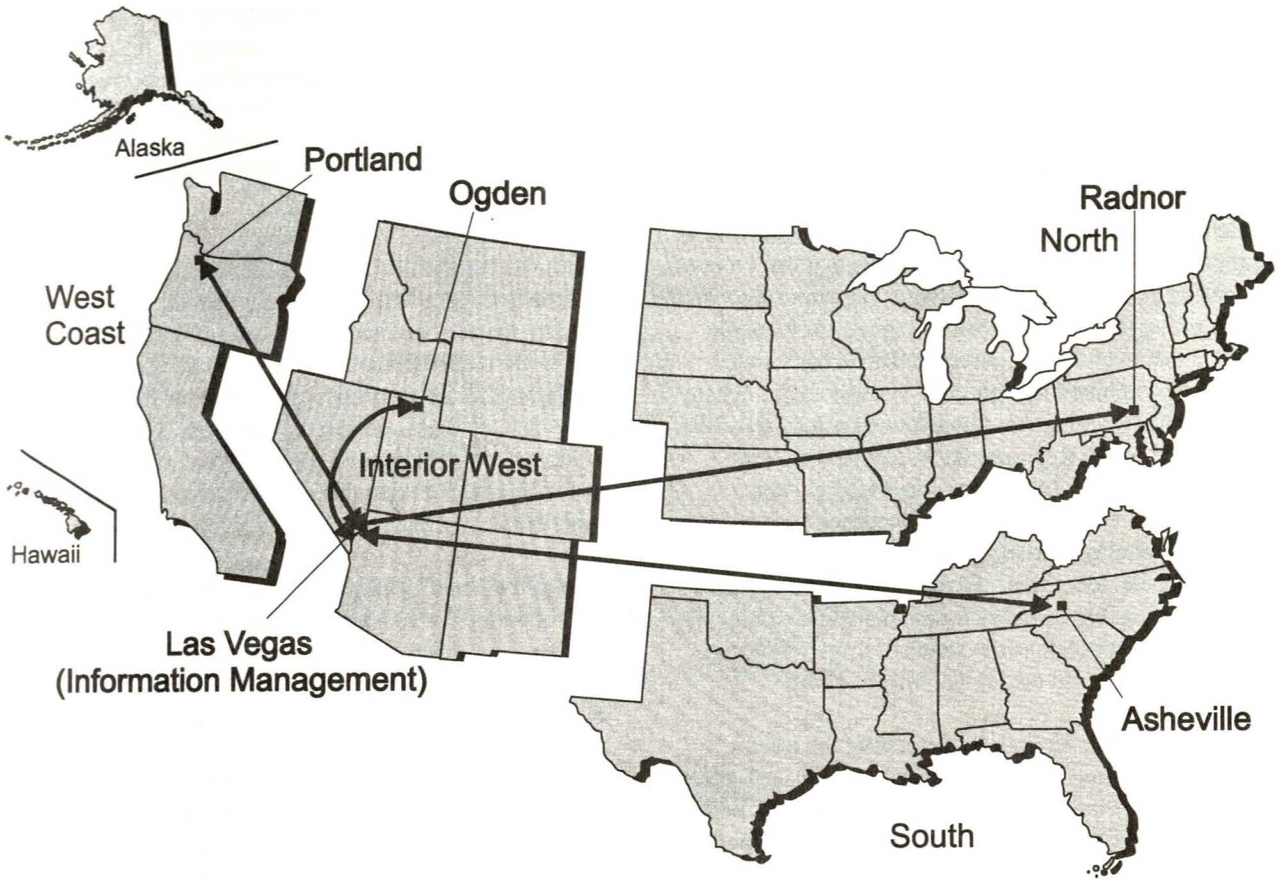


Figure 2.—*Forest Health Monitoring regions, regional offices, and national office locations.*

State Foresters (NASF), a Bureau of Land Management representative, and the national Forest Inventory and Analysis (FIA) manager. If consensus cannot be reached, an issue is forwarded to the FHM Core Team, consisting of the national manager, the four regional managers, and the NASF representative. Strategic oversight is provided by an FHM Steering Committee, consisting of the Associate Deputy Chiefs for Research, National Forest System, and State and Private Forestry of the FS, and the Chairs of the NASF Forest Health and Research Committees. Day-to-day operations at the national level are run by the national manager (located in Washington, DC) and the national office staff, located in Research Triangle Park, North Carolina. The national manager reports to the Director of the Southern Research Station, located in Asheville, North Carolina.

QUALITY ASSURANCE

The FHM program maintains a strong emphasis on quality assurance. All trainers for field data collection are certified, and all field crew members are certified after successfully completing a training program. Data are collected on portable data recorders that include substantial internal validation checks to prevent entry of aberrant values. Crews are audited throughout the season in blind checks (the field crew does not know which plot will be audited), and reference plots are established across the country to compare accuracy. All indicators have specified measurement quality objectives and data quality objectives. Each indicator is peer reviewed before implementation, and the overall program has been reviewed by the National Research Council (Committee to Review the EPA's Environmental Monitoring and Assessment Program 1994).

CENTRALIZED INFORMATION MANAGEMENT

Another advantage of FHM is that all data are processed at one central location in Las Vegas, Nevada. We use a relational database—Oracle platform. This provides consistency and efficiency, and it greatly improves our quality assurance. Improvements and standardized protocols can thus be implemented simultaneously across the country with this approach.

RESULTS TO DATE

A variety of reports has been produced to date. These reports have focused necessarily on current status rather than trends. The scale of these reports is national and regional—not local. The FHM grid system cannot by itself be used to address local issues. Only now are we beginning to focus on trends because we now have an 8-year collection of annual measurements that can be used to discern trends. The current status indicators for visual crown rating for the FHM North Region, for example, indicate that over 96 percent of the hardwoods and softwoods combined had good or average crown density, crown dieback, and crown transparency across all of the states in the North Region in 1996 (Stoyenoff *et al.* 1998a-c). For this same region, the FHM damage indicator shows that 80 percent of the trees have no discernible damage. Also, ozone damage to bioindicator plants has been identified. To provide a more complete portrayal of health, in future assessments we will incorporate other factors such as the status of invasive species, weather patterns, and ecological information.

In the FHM South Region, 97 percent of the trees measured had good or average density in 1993, 98 percent had normal transparency (0 to 30 percent) and 98 percent had good or average crown dieback (less than 20 percent) (Burkman *et al.* 1996). More recent data are currently being analyzed and reported.

In the FHM Interior West Region, only 1 percent of the trees measured had dieback and transparency exceeding 25 percent (low values indicate vigorously growing trees), and 96 percent had crown density between 25 and 75 percent (high values indicate vigorously growing trees during the 1992-95 baseline reporting period. There were, on average, 10 epiphytic macrolichen species per plot, with 90 species identified in total. In downtown Denver, only two lichen species were detected on a forested plot, thus lichens may be a powerful indicator of atmospheric pollution. Exotic plant species accounted for about 4.5 percent of all plant species and 1.5 percent of the plant cover, the lowest value for any region in the country (Rogers *et al.* 1998).

In the FHM West Coast Region, we currently have data only for California, which entered the program in 1991. Oregon and Washington entered in 1997. In California, the baseline data, collected between 1992 and 1995, showed that 90 percent or more of the trees measured had good or average crown density (above 20 percent—high values indicate vigorously growing trees), but timberland oaks and pines had low values only for crown density on average (Dale 1996). The relatively lower values for these species need further clarification, because many factors, including weather effects, can create these patterns. About 80 to 90 percent of the trees had dieback less than or equal to 5 percent and 95 percent of the trees had good or average crown transparency (between 0 and 30 percent). About 70 to 75 percent of the trees were damage free. Exotics make up 13.2 percent of all plant species and were responsible for about 25 percent of the forest cover, the highest value for any region in the country (Rogers *et al.* 1998).

Aerial survey results (table 2) show that on average, 21 million acres of a total of 740 million total forested acres nationwide are defoliated each year (during 1986-1995) due to the combined activity of five major insects—gypsy moth, southern pine beetle, mountain pine beetle, spruce budworm, and western spruce budworm. We are currently working on digitizing and mapping current and previous years' data and linking them to the Detection Monitoring plot data.

One of the benefits of the FHM program is that the data are collected in a standardized way with nearly the same protocols used across the country and in six other countries. This allows us to make interregional and international comparisons.

We are now beginning to assess change across sampling years. Knowing current status is important, but knowing the trends of indicators is just as important, or perhaps more important. For example, indications are there will be some areas that have experienced sizable increases in the amount of crown dieback during the last 6 years. This may present a different picture compared to the earlier data for current status, but we have not finished these analyses yet. Preliminary data analysis (fig. 3) shows areas outlined in red where dieback for softwoods from 1991 to 1997 has increased from 5 to 17 percent on an average ecoregion basis. This is a biologically and statistically significant amount. We will continue to investigate and report on these analyses as they are done. We intend to relate FHM indicators to other stressor information such as air deposition data, Palmer Drought Index, aerial survey Detection Monitoring data, and FIA data, to produce truly integrated assessments. Once the assessments are made, the implications for management and strategic policy can be determined.

INITIATING THE EVALUATION MONITORING PHASE

In 1998, there were sufficient resources to begin the Evaluation Monitoring phase of FHM. Projects were submitted to the national office for competitive peer-review. A series of projects was selected that identified problematic situations in the field based upon Detection Monitoring data that warranted further evaluation. A list of the top projects follows:

1. Evaluation of Lake States Basswood Decline

Table 2.—*Acres of insect activity by years (in 1000 acres)*

Year	Gypsy moth[a]	Southern pine beetle[b]	Mountain pine beetle[c]	Spruce budworm[a]	Western spruce budworm[a]
1986	2,413	26,389	3,450	1,042	13,223
1987	1,329	13,796	2,442	680	7,953
1988	709	7,936	2,206	265	6,063
1989	2,996	5,333	1,614	145	3,140
1990	7,304	4,232	936	201	4,632
1991	4,152	10,744	617	108	7,171
1992	3,057	14,307	641	126	4,594
1993	1,784	10,414	782	116	447
1994	880	5,251	405	778	496
1995	1,418	21,676	576	569	478
Total	26,042	120,078	13,669	4,030	48,197
Average	2,604	12,008	1,367	403	4,820

[a] Acres of aerially detected defoliation.
[b] Acres of host type with one or more multiple-tree spots per 1,000 acres.
[c] Acres of host type with one dead or dying tree per 10 acres.

Source: Forest Insect and Disease Conditions in the United States, reports 1986-95.

2. Evaluation of Sugar Maple Decline in Pennsylvania

3. Evaluation Monitoring of Coastal Forest Health in Florida

4. Aerial Survey and Ground Verification to Monitor Swiss Needle Cast in Coastal Oregon and Washington

5. Fire Risk Rating of FIA/FHM Plots in Evaluation Monitoring (Interior West Region)

Other projects are also being funded within each FHM Region. After 2 to 3 years, we will evaluate these Evaluation Monitoring projects to determine if they satisfactorily resolved the issue or if they need to be referred to ISEM sites.

UNIQUE FEATURES OF FHM

FHM is a nationally standardized monitoring system providing annual information on forest ecosystem health that can be used in a variety of assessment reporting venues. These include reporting on the Santiago Declaration of Sustainable Forest Management (Criteria and Indicators), the Resource Planning Act Assessment (RPA), the Environmental Report Card, various reports to Congress from the Chief of the FS, and others. The value of a standardized protocol where data can be aggregated is enormous. We have too many examples where regional programs had difficulty aggregating data to provide a broad national picture because of disparate measurement protocols.

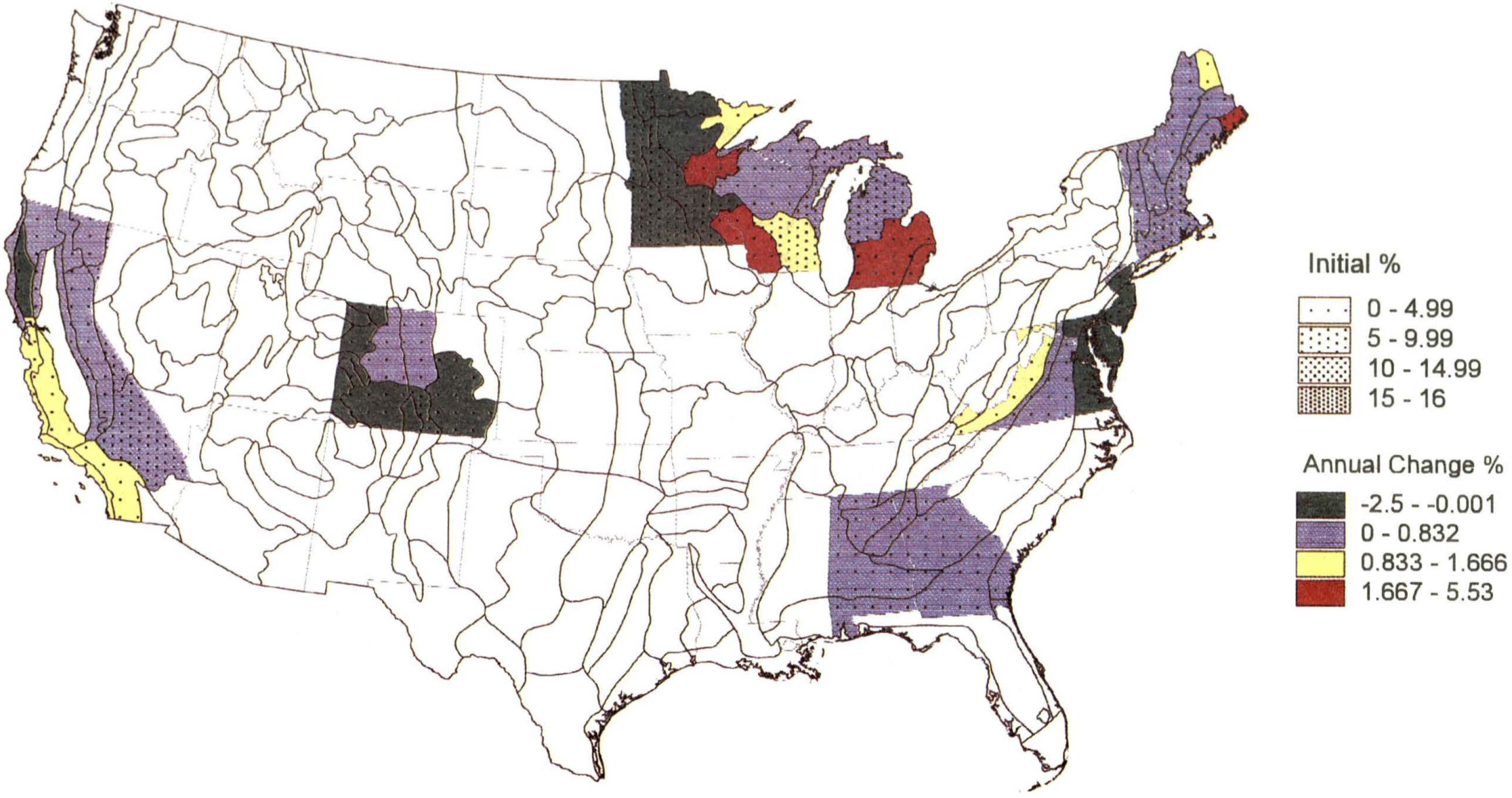
The data collected in FHM are ecologically robust. FHM collects a broad suite of indicators related to forest ecosystem condition. These indicators are needed to portray a complete picture of ecosystems, the kind of information for which our constituents and partners are asking.

Although FHM provides national and regional information only, there is direct value to local managers in three main categories.

1. Local areas or states can intensify the plot system to provide fine-scale information. This is currently being done in a several places, most notably on the Allegheny National Forest (John Palmer, Forest Supervisor, Allegheny National Forest, Warren, PA, personal communication).

2. Local areas or states can use the FHM protocols for local needs, even if they are not involved in the FHM Detection Monitoring grid. This is being done in Region 6 of the FS, where the lichen protocols are being used on six national forests "off grid." It allows managers to link their data results with the national results of FHM's lichen indicator. Why should local jurisdictions develop their own protocols when FHM has already spent many dollars developing peer-reviewed methods?

Dieback: Initial Value and Annual Change
Softwoods by Ecosection


Initial %
0 - 4.99
5 - 9.99
10 - 14.99
15 - 16
Annual Change %
-2.5 - -0.001
0 - 0.832
0.833 - 1.666
1.667 - 5.53

Dieback is a measure of the percentage of small dead branches on the sun-exposed portion of the crown.

These estimates were derived using measurements taken at FHM sites between 1991 and 1997:
East (1991-1997); CO and CA (1992-1997); Lake States (1994-1997)

Estimates for each Bailey's Ecosection were derived by GLS using SAS PROC MIXED

Figure 3.—*Dieback: Initial value and annual change—softwoods by ecosection (1991-1997).*

3. Even if the scale of inference of the FHM program is regional, it provides an ecosystem-wide context for showing how a local unit's ecological condition fits in with the larger ecoregion condition, which will be invaluable to local area managers.

FHM is in the process of merging its plot component of Detection Monitoring with the FIA program. Currently the two programs are using the same sampling design (FHM's current design) and are attempting to relocate plots on the same plot centers. Taken together, the two programs will provide invaluable information on an annual basis to various stakeholders. FIA is contemplating moving to an annualized cycle (like FHM) in which some plots are sampled every year in all 50 states. By having FHM plots as a subset of the more spatially intense FIA plots, FHM and FIA will be very effective in meeting many of the nation's inventory and monitoring needs.

CONCLUSION

Forest health is a topic on most people's radar screens in the natural resource community. We believe that it is essential to have the proper information to make accurate resource management decisions. Before the advent of FHM, management decisions were based on a FS aerial survey program that was not standardized (FHM has now standardized it) and other information that was not standardized or not always quantified. FHM, combined with FIA, will provide quantitative, standardized information on the nation's forestland resources. How the FS, other agencies, and society at large decide to use the data is another issue. We want to be the purveyors of the information, similar to the economic indicators that are reported monthly in the lower left corner of the first page of USA TODAY. We would like to provide some of the list of leading Environmental Indicators to our constituents.

FHM has made great strides in expanding the permanent grid system and is poised to be able to provide information for all 50 states. The grid currently covers about 60 percent of the forestlands of the lower 48 states, and the plan for fiscal year 1999 is to increase this to about 70 percent. Once the Detection monitoring grid is in place in all 50 states and we fully implement Evaluation Monitoring and ISEM, we will be able to provide an annual picture of status and trends for specific attributes on all of the nation's forestlands in a standardized manner—something that currently still eludes us. This will greatly increase our ability to report confidently about the health and condition of the nation's forests, as well as improve our ability to manage forests on a more sustainable basis.

ACKNOWLEDGMENTS

The following people reviewed this paper: Dr. Barbara Conkling, North Carolina State University. Raleigh, NC, USA; and Dr. Jack Waide, USDA Forest Service, Washington, DC, USA.

LITERATURE CITED

Burkman, W.G.; Vissage, J.S.; Hoffard, W.H.; Bechtold, W.A. 1996. Summary report—forest health monitoring in the South, 1993 and 1994. Resour. Bull. SRS-32. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 91 p.

Committee on the Environment and Natural Resources. 1997. Integrating the nation's environmental-monitoring and research network programs—a proposed framework. Washington, DC: National Science and Technology Council. 103 p.

Committee to Review the EPA's Environmental Monitoring and Assessment Program. 1994. Review of EPA's Environmental and Monitoring Assessment Program: forests and estuaries components. Washington, DC: National Research Council. 99 p.

Dale, J. 1996. California forest health in 1994 and 1995. Publ. R5-FPM-PRR-002. SanFrancisco, CA: Pacific Southwest Region. 63 p.

Kolb, T.E.; Wagner, M.R.; Covington, W.W. 1994. Forest health from different perspectives. In: Eskew, L.G., comp. Forest Health through silviculture: proceedings of the 1995 national silviculture workshop. Gen. Tech. Rep. RM-267. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest Experiment Station: 5-13.

Mangold, R.D. 1995. Sustainable development—the Forest Service's approach. Journal of Forestry. 93(11): 25-28.

Montreal Process. 1995. Criteria and indicators for the conservation and sustainable management of temperate and boreal forests. Hull, Quebec, Canada: Canadian Forest Service. 27 p.

Rapport, D.J.; Reigier, H.A.; Hutchinson, T.C. 1995. Ecosystem behavior under stress. American Naturalist. 125: 617-640.

Rogers, P.; Schomaker, M.; McLain, W.; Johnson, S. 1998. Colorado Forest Health Report—1992-95: a baseline assessment. Fort Collins, CO: Colorado Forest Service. 44 p.

Smith, W.D.;Gompertz, M.L.; Catts, G.P. 1998. Analyzing the precision of four sampling designs for forest health monitoring. (in submission to Forest Science).

Stoyenoff, J.; Witter, J.; Leutscher, B. 1998a. Forest health in the mid-Atlantic. [unnumbered publication]. Ann Arbor, MI: University of Michigan, School of Natural Resources and Environment. 31 p.

Stoyenoff, J.; Witter, J.; Leutscher, B. 1998b. Forest health in the New England States and New York. [unnumbered publication]. Ann Arbor, MI: University of Michigan, School of Natural Resources. 31 p.

Stoyenoff, J.; Witter, J.; Leutscher, B. 1998c. Forest health in the Neorth Central States. [unnumbered publication]. Ann Arbor, MI: University of Michigan, School of Natural Resources. 31 p.

USDA Forest Service. 1998. Forest health monitoring 1998 field methods guide. Research Triangle Park, NC: U.S. Department of Agriculture, Forest Service.

World Commission on Environment and Development. 1987. Our common future. Oxford, UK: Oxford University Press.

A Prototype for Forest Health Monitoring in Indiana State Parks

Rachel Morse, KaDonna Randolph, and John W. Moser, Jr.

Abstract.—In 1997, 25 Forest Health Monitoring (FHM) plots were established in two Indiana state parks and a nearby parcel of privately owned land using a new protocol that differs from the systematic grid of the national program. All plots were reassessed in 1998. Data analysis focuses upon establishing baseline conditions for the study sites and providing relevant information for park management.

Indiana joined the National Forest Health Monitoring Program in 1996 with 144 plots from the national EMAP grid. Due to the agricultural and urban fragmentation typical of midwestern states, only 38 of those 144 plots actually contain at least one forested condition. Many of Indiana's forests are not well represented in the FHM data set, including forests within the boundaries of Indiana state parks. In fact, no systematic statewide forest inventory or monitoring program exists in Indiana state parks. Despite a mission statement that charges the Division of State Parks to protect places of natural heritage and biologic importance, much information about these forests has not been collected.

In 1997, this pilot FHM intensification project began with two objectives: (1) To create a protocol for installing off-grid FHM plots in small study areas to augment the FHM program in Indiana, and (2) To establish a baseline of forest health information in two Indiana State Parks that will provide management information for the Division of State Parks. This project represents one of the most intensive uses of off-grid FHM plots for a natural resource management study.

STUDY SITE DESCRIPTION

Three study sites were chosen: two state parks with a "hands-off" management plan and a selectively harvested private property. Practicality prevailed in site selection. Shades and Turkey Run State Parks contain large forested areas. They are located 15 miles apart and within 50 miles of Purdue University. The private property in Annapolis, IN, is within 21 miles of both parks and has similar topography and forest cover. All sites lie in the Sugar Creek watershed, contain steeply sloping ravines (measured slopes range from 0 to 73 percent), and have glacial soils. Elevations range from 500 to 700 feet above sea level. All plots are located on sawtimber-size stands of natural origin with stand ages ranging from 50 to 120 years.

OBJECTIVE 1: CREATING A NEW PROTOCOL

Plot Location

Plots were located only in forested areas on both parks and the private property. Plots in the parks were located only in high-use recreation areas because of park managers' interest in the impacts of recreation on forest health. For this study, high-use recreation areas have been defined as within 300 feet of a trail, campground, shelter, or other park construction.

Due to the limited time in which FHM data can be collected (after full leaf-out and before fall coloration), a limited number of FHM plots could be established. Time, budget, and labor considerations restricted the number of plots to 25 (10 in each park and 5 in the private property). This number of plots was not enough to systematically assess the forested areas within the parks. Therefore, a random plot allocation method was created.

Plot Location Procedure

1. Grids of 5.25 acres were placed over aerial photos of the study sites. This was the minimum size allowing for plots located in adjacent grids not to overlap.

2. Areas that would not qualify as a forested condition for FHM protocol were eliminated, as well as low-use recreation areas in the parks.

3. Grid squares falling over acceptable conditions were numbered sequentially from west to east and north to south.

4. Random numbers were used to select grid squares for plots. Squares that fell in stands where the estimated age was less than 50 years were eliminated.

5. The center of each grid square was located on the ground, and a random azimuth and a random distance from the center (less than 200 feet) were taken. This became the center of the FHM plot.

Research Assistant, Research Assistant, and Professor of Forest Biometry, respectively, Purdue University, West Lafayette, IN, USA.

OBJECTIVE 2: BASELINE FHM DATA

Forest health assessments can provide baseline data for state park forests. While it is important to have information about species composition, stand densities, damages, etc., the value of a forest inventory is in the continued reassessment and the comparability of assessments in different forests under a variety of management schemes. To provide the most useful baseline data for the Division of State Parks, we decided that the forest health assessments had to be repeatable and linked to a national monitoring program. We chose the National Forest Health Monitoring Program because of the interests of this program and of the Indiana Division of Forestry in increasing the number of forested FHM plots in Indiana. This well-established program has detailed measurement protocols.

Field crew members were trained and certified in FHM survey procedures at the USDA Forest Service Northern Region training sessions before the field seasons. All protocols from the Field Methods Guide (USDA Forest Service 1998) were followed, and data for all health indicators of the national program (mensuration, crowns, damage, soils, and lichen) were collected. However, we had to modify two protocols for plots in the state parks.

Trees and saplings in Shades State Park could not be painted at dbh due to the potential to negatively impact visitors' experiences if paint slashes could be viewed from trails. Site trees located in the nature preserves within each park (2 site trees in Shades and 10 site trees in Turkey Run) could not be cored to determine age at dbh. Ages for these site trees were estimated using written histories of the areas and cores of dead trees in the preserves.

RESULTS AND DISCUSSION

The data set for this project contains 93 forested subplots yielding a total of 499 trees. This distribution among sites is as follows: Shades: 38 forested subplots, 220 trees; Turkey Run: 38 forested subplots, 192 trees; Private Property: 17 forested subplots, 87 trees.

In addition to tree data, sapling, seedling, microplot, soil, and lichen data have been gathered for these plots. Listing the entire data set in this section would not be as useful as examining specific portions of the data with applications for park management. So, the following are three examples of specific applications of FHM data.

Defective Trees

Defective trees, those with damages that compromise structural integrity, are of great interest to park managers. Not only do defective trees affect visitors' perceptions of the forest's condition, but these trees have the potential to become hazard trees. A hazard tree is any defective tree with a high risk of causing injury to people or damage to property. Defects that could create hazard trees include decayed wood, cankers, root problems, dead branches, and cracks and seams (Albers and Hayes 1993).

The FHM Damage and Catastrophic Mortality Assessment makes it possible to list the defect trees located in each plot. Table 1 was constructed for the FHM plots in the parks based on the 1997 assessment. Cracks and seams were added to the assessment list in 1998; the data are not yet available.

Table 1.—*Number of trees assessed in Shades and Turkey Run State Parks, Indiana, with defect damages (1997)*

Defect	Number of trees
Decayed wood	85
Cankers	8
Broken roots	2
Dead branches	16

Special attention can also be given to species with particular damage problems, such as American beech (*Fagus americana*). The smooth bark of beech is often the target of tree carvers, especially when the trees are located along trails. Cuts deep into the cambium can become decay sites. Beech trees on park FHM plots have a 51.5-percent occurrence of decay compared to 18-percent occurrence for all other species combined. This finding may prompt further investigation into the detrimental effects of tree carving in these parks.

Mast-Bearing Trees

Wildlife viewing is a key attraction in Indiana state parks. One way to ensure the presence of wildlife in the parks is to provide the proper habitat, including food. Maintenance of mast-bearing species (including oaks (*Quercus* spp.), hickories (*Carya* spp.), and beech) is important for mast-dependent wildlife such as squirrels (*Serius* spp.), chipmunks (*Tamias striatus*), turkey (*Meleagris gallopavo*), and white-tailed deer (*Oedocoileus virginianus*), which derive a portion of their diets from mast.

A management strategy that favors shade-tolerant species such as maples and beech over oaks may cause a reduction in the production of mast (Mannan *et al.* 1996). Examination of seedling, sapling, and tree data from a per acre standpoint yields information about species composition (table 2).

Table 2.—*Number of maple, oak, hickory, and beech seedlings, saplings, and trees per acre in Shades and Turkey Run State Parks, Indiana, based on 1997 FHM assessment*

Species	Tree type	Number/acre	Species	Tree type	Number/acre
Maples (*Acer* spp.)	Seedling Sapling Tree	213 95 34	Oaks	Seedling Sapling Tree	12 0 16
Beech	Seedling Sapling Tree	103 16 10	Hickories	Seedling Sapling Tree	32 8 8

The comparatively few oak and hickory understory trees (no oak saplings were recorded on park plots) may signal a shift in species composition that is detrimental to mast-dependent wildlife. This is an issue park managers may wish to address.

Tree Crowns

Tree crowns shape the canopy structure, determine the light intensity beneath the canopy, and contribute to the amount of individual tree growth. All of these are important considerations for aesthetic value as well as health. Not only do poor crowns have a negative effect on tree vigor, but they also can decrease the visual enjoyment of people recreating in the woods. Even forest damages of less than 10 percent severity can have a negative effect on visual quality for the average recreationist (Buhyoff and Leuschner 1978). FHM evaluations provide appraisals for crown density, foliage transparency, and crown damages. These variables can be examined for certain plot locations or for certain species. Summaries such as figure 1 can be constructed to search for areas or species with visual quality problems.

CONCLUSION

The plot location protocol initiated in this project provides a method to locate FHM plots on specific study sites that guarantees the area of interest (such as high-use recreation forests) will be sampled. The plots established in this project provide baseline data for important landscapes missed by the systematic grid. In addition, comparisons

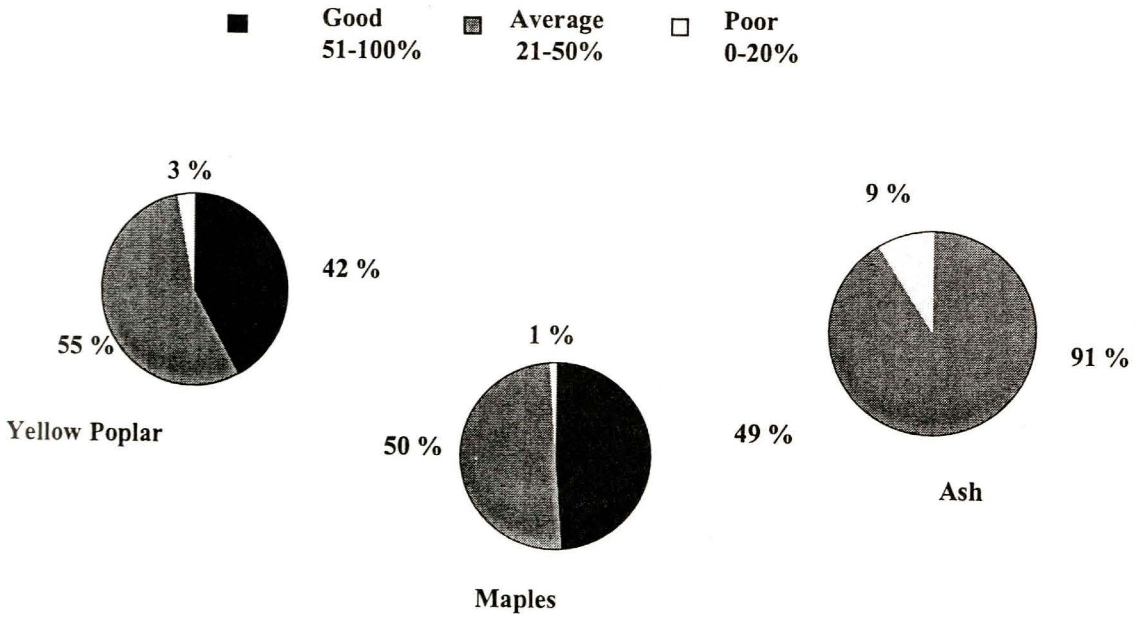


Figure 1.—*Crown densities for yellow poplar (*Liriodendron tulipifera*), maples, and ash (*Fraxinus *spp.) on FHM plots in Turkey Run and Shades State Parks, Indiana.*

can be made between the "preserved" forests of the park and other FHM plots. By linking the forest health plots in our study sites to the nationwide system of FHM plots, we can enhance both the local monitoring project and the national program.

ACKNOWLEDGMENTS

The authors thank the Indiana Department of Natural Resources Division of State Parks, Indiana Department of Natural Resources Division of Forestry, USDA Forest Service National Forest Health Monitoring Program, and USDA Forest Service Forest Inventory and Analysis Program for their support of this research effort.

LITERATURE CITED

Albers, J.; Hayes, E. 1993. How to detect, assess and correct hazard trees in recreational areas. Minnesota: Minnesota Department of Natural Resources. 63 p.

Buhyoff, G.J.; Leuschner, W.A. 1978. Estimating psychological disutility from damaged forest stands. Forest Science. 24(3): 424-432.

Mannan, R.W.; Conner, R.N.; Marcot, B.; Peek, J.M. 1996. Managing forestlands for wildlife. In: Research and management techniques for wildlife and habitats. Lawrence, KS: Allen Press, Inc.: 689-721.

USDA Forest Service. 1998. Forest health monitoring 1998 field methods guide. Research Triangle Park, NC: U.S. Department of Agriculture, Forest Service, National Forest Health Monitoring Program.

Setting Monitoring Objectives for Landscape-size Areas

Craig M. Olson and Dean Angelides

The setting of objectives for monitoring schemes for landscape-size areas should be a complex task in today's regulatory and sociopolitical atmosphere. The technology available today, the regulatory environment, and the sociopolitical considerations require multiresource inventory and monitoring schemes, whether the ownership is industrial or for preservation. Monitoring is essential so that we know if we are meeting our management objectives.

Monitoring is the basis of adaptive management. In consideration of the pressures to know if we are headed in the right direction with our land management, monitoring becomes an integral part of a land plan. Regulatory agencies consider a plan to be a contract based on adaptive management. It allows us to move forward in the face of uncertainty.

Human influences are great everywhere on earth. Action or no action, both have a significant effect on some, most, or all resources. So even preservation areas need management plans and monitoring schemes.

So, the crux of this presentation is "What do I need to know to set up an effective monitoring program?" or "How do I set up a useful monitoring program?"

Key in this effort is to avoid collecting a lot of useless information. That should be one of the main objectives along with collecting enough information to be meaningful. What's meaningful and what's useful should be well thought out well in advance. We can certainly collect mounds of data.

And, of course, we all know what we want to measure and how we think we ought to measure it, but careful consideration of the appropriate analytic approach, be it statistical or otherwise, may change our priority for measurement.

There are some things that we would like to know, but getting that information or enough of the information to be worthwhile is so expensive that we must postpone measurement until the technology or collective desire permits us to get the information.

VESTRA Resources, Inc., Redding, CA, USA.

First, we need to identify what needs to be collected, that is, who needs what information. We must provide for:

- Management Needs
- Regulatory Needs
- Sociopolitical Needs

What's meaningful and what's useful depends on one's needs. Management or planning needs necessitate a certain approach. Private timberland owners often want to know how much timber they have and what kind of growth they have to supply their mills. These same timberland owners now must often meet regulatory requirements of sustainability with respect to timber yields and also sustainability of habitat. And government regulators push to err on the conservative side, calling into question habitat models and growth and yield models. Sociopolitical pressures are also calling for conservative planning approaches.

A monitoring program may have many components. For example, a monitoring scheme might include:

- Plot data for vegetation
- Camera stations for wildlife occurrence
- Trapping grids for wildlife
- Stream temperature probes
- Transect of woody debris in the uplands or streams
- Fish trap counts
- Remotely sensed resources

And there are many, many, many more. Each type of organism or physical condition could and probably should be tracked at some level. But we can't measure everything.

Next, we want to define why we are collecting information. It may be for:

- Point Estimation
- Change Detection
- Resource Modeling
- Model Validation

Each of these can necessitate a different statistical or sampling approach.

Setting priorities and defining the overall objectives can be the most tedious part of the whole inventory and monitoring program. We say this because in today's regulatory and political environment there are pressures to measure or monitor everything as well as pressures to improve or validate existing models for resource projections or to develop new models. This can be very costly. In no way could we begin to help resource managers weigh and balance demands for information. What we can do is help develop a process for implementing the highest priorities for monitoring and integrating them into an efficient system.

Today's land management requirements necessitate monitoring for multiple objectives. Of course, we monitor for multiple objectives; we've always wanted to get information on a number of variables when we monitor. If it's timber, we want to know volume, growth, defect, and size distribution. If it's wildlife, we want to know number, age distribution, sex distribution, and condition.

But in the past, monitoring schemes focused on one or maybe two variables to achieve target precision. We can assign a target precision for every variable or at least know what kind of precision to expect. Once we know what information we can get and what information we want to get, we can choose and adjust.

Each component may require a different statistical or analytical approach. But these approaches can be integrated together. Point estimation and change detection involve collecting data in an unbiased fashion. Often we want to use stratified sampling that can minimize effort where there is low occurrence of the population. On the other hand, model development and validation requires data collection across the range of conditions, even targeting the extreme conditions to "nail down" the extremes in the model so that the model will behave well through the range of conditions in which it is intended to be used.

First, we want to define the all populations to be monitored. Defining the populations to be monitored usually begins by prioritizing information needs, that is, sensitive species or resources, etc. This might be a population of stream temperatures, a population of timber volumes, a population of slime molds, or a population of migrating fish. The information may be count data (number of organisms) and/or measure data (weight of organisms).

We need to choose one or many analytic approaches. They may be different for different components in the monitoring scheme. For example, we might choose:

- Multiple Comparisons
- Trend Analysis
- Regression Analysis including ANOVA/ MANOVA, linear and non-linear models
- Change Detection (Remote Sensing)

It is imperative that the analytic approach be well thought out before going into the field, whatever the approach. Without clearly defined analyses detailed ahead of time, we'll get a lot of useless data.

We need to consider the timing of measurement or remeasurement for each component. How often should we measure a particular component to be monitored? Not all resources need to be measured equally often. Great savings might be made if we can forego measuring some components each time we want to measure.

And, of course, we want to maximize our monitoring dollars. A well-coordinated approach, well thought out in advance, will ultimately cost less.

We need to incorporate all available information into our design.

- For each measure to be tracked, compute variance/standard error
- Use different sampling unit sizes, if possible
- Use a pilot study to determine appropriate sampling unit size and shape

For each variable to be measured, we want to be able to achieve a certain precision, be it for a point estimate or for a model. Varying the sampling unit size can help economize to achieve the best precision for the least cost. If we don't have good information about a certain resource to be tracked, then a pilot study, investigating variance with respect to sample size, sampling unit size, travel time, and plot location, can save time and effort later.

Again, we want to assign a target precision for each component to be monitored. Whether we can achieve all the targets or not, it's best to know what the tradeoffs are in advance and at least make informed decisions. What is the appropriate confidence interval for each measure? Confidence limits could, and may very well likely, be different for each component.

Assign a measurable difference to detect. How much of a change do you want to be able to detect, statistically, that is? With forest inventory, we would often target a certain confidence interval for a given probability. And if we measured an ownership once, we would get one answer. And if, at some time in the future, we measured the ownership again we would get another answer, both within the specified target precision. Was there a significant change? The precision targets for a single point estimate will unlikely provide sufficient power for finding if the two estimates are statistically different. This may not be important for timber resources, but it might be very important for rare resources that might be impacted by management.

The sampling strategy should consider:

- Sample Size
- Sample Unit Location (Travel time versus variance)
- Sample Unit Size and Shape

As we move towards developing a monitoring strategy, we must look at, and juggle, the various components of sampling. Before we decide on a final scheme, it is probably best to develop several sampling scenarios for each resource to be monitored, so that a strategy can be adjusted when we make our final plan of action.

And now we'll want to integrate the various sampling approaches. Integrating the monitoring scheme means that once we have identified all the things we want to measure and once we have calculated the sampling unit size, sample size, sample allocation method, and sampling frequency for each of these things, we must integrate them into an efficient system, minimizing cost and effort. The overall available budget for monitoring will dictate the level of priorities that can be met. This will usually involve tradeoffs, but of course we begin by including the highest priority things and the requisite sampling approach for them first.

And finally, monitoring schemes can be adaptive. That is, in the future we can modify the scheme as better information becomes available. We'll want to maintain the statistical validity of our scheme, but there are opportunities to reduce the sample size or reduce the frequency of measure. How we set the criteria for modification should be spelled out at the outset, so that we have some understanding of where we are going.

So, as we set objectives for monitoring, we should keep in mind that these priorities can and do change as we know more about the sensitivity of resources and as the technology for measurement improves.

As we stated at the outset, the setting of objectives for monitoring schemes for landscape-size areas can and should be complex. The technology available today, the regulatory environment, and the sociopolitical considerations all require the use of multiresource inventory and monitoring schemes. Such monitoring is essential so that we know if we are meeting our management objectives. A carefully conceived monitoring plan will help minimize data collection costs and provide the information needed for land management decisionmaking.

Boundary Plot Corrections for Variable Radius Plots—Simulation Results

Margaret Penner and Sam Otukol

Abstract.—The boundary plot problem is encountered when a forest inventory plot includes two or more forest conditions. Depending on the correction method used, the resulting estimates can be biased. The various correction alternatives are reviewed. No correction, area correction, half sweep, and toss-back methods are evaluated using simulation on an actual data set. Based on the simulation results, no correction is recommended when the boundary between forest conditions is gradual. For abrupt boundaries, either the area correction or toss-back methods should be used.

THE PROBLEM

Forest inventory generally involves delineating relatively homogenous forest units (stands) or confirming existing stand boundaries, locating ground sampling plots and measuring some forest attributes on these plots. Alternately, ground plots can be located and measured first and the resulting data used alone to estimate forest attributes.

If the plots are randomly located within the stand, some will include the stand boundary and portions of the adjacent area. Analysis of the field data is complicated by these boundary plots that include one or more borders between stands and measurements corresponding to two or more stands. When plots are constrained to fall entirely within a single stand, the trees near the stand boundary have a lower probability of being sampled. If the stand characteristics near the boundary differ from the stand interior, the resulting stand estimates are biased. Various methods have been suggested to deal with this boundary plot problem (e.g., Forest Science Monograph 31, Iles (1993)), each with associated advantages and disadvantages. This report reviews the alternatives and, using simulation, quantifies the errors associated with some of these techniques for variable radius plots.

The seriousness of the boundary plot problem depends on the magnitude of the edge effect between forest conditions and the proportion of sample plots that include two or more forest conditions. The number of boundary plots depends on the size of the plot and the amount of stand edge relative to stand interior. In some landscapes, more than 30 percent of the sample plots may be boundary plots (Birdsey 1995), and biases of more than 6 percent may result from moving plots away from the boundary (Williams *et al.* 1996). Based on data from various sources, Hahn *et al.* (1995) reported that 2 percent of subplots within 1-acre cluster plots will straddle two or more forest conditions. In the two 8-ha (rectangular) forests studied by Ashley and Beers (1970), over 60 percent of the sample points required some correction for boundary overlap. Ignoring the boundary will introduce bias to the stand and strata estimates, but as population size increases, the bias should become negligible as the probability of locating plots along the population boundary decreases.

The boundary plot problem is confounded by the subjectivity involved in delineating stands (Fortin 1997) and the potential introduction of error when transferring hand-drawn boundaries from an aerial photograph to a digital database. The complications to the boundary plot problem arising from a vague or inaccurate stand boundary are not discussed here.

METHODS FOR DEALING WITH EDGE PLOTS

In practice, one of the main difficulties in dealing with edge plots in the field is identifying and locating the boundary. When the boundary is obvious in the field (e.g., forest - nonforest boundary), one or more of the following alternatives may be appropriate. However, even abrupt boundaries are generally not straight, sharp lines. For gradual transition zones or ecotones, the bias incurred by ignoring the border may be smaller than the uncertainty associated with locating the border in the field.

Each alternative may be most appropriate in some circumstances, with certain attributes. The challenge in inventory design is to select a method yielding generally robust results in most situations and consistent results in all situations. Alternatively, rules can be constructed to determine which option to use in specific circumstances. In evaluating the alternatives, some measurable edge effect is assumed. Otherwise, although some methods may yield biased stand estimates, given a statistically

---

Respectively, Forest Biometrician, Box 407, R.R. 4, Huntsville, ON, Canada P1H 2J6 Ph/Fax 705-635-9413, e-mail: mpenner@vianet.on.ca, and Forest Biometrician, Inventory Branch, British Columbia Ministry of Forests, 722 Johnson Street., Victoria, BC, Canada V8W 3E7.

Table 1.—*The advantages and disadvantages of the various boundary corrections are given. Some degree of edge effect (ecotone) is assumed.*

Correction method	**Advantages**	**Disadvantages**
Ignoring the boundary	The chief advantage is simplicity. This alternative may be appropriate when the transition between stands is gradual (minimum bias) and the boundary is difficult to locate in the field. Unbiased at the population level.	Bias and imprecision at the stand and subpopulation levels. In general, stands appear more heterogeneous than they are.
Moving the plot (substitution)	Simple to implement. Unbiased at the population level.	The undersampling of conditions near the stand boundary leads to bias at all levels of inventory aggregation and incorrect estimates of the within and between stand variability.
Dropping the plot	Simple to implement. Unbiased at the population level.	The undersampling of conditions near the stand boundary leads to bias at all levels of inventory aggregation and incorrect estimates of the within and between stand variability.
Area correction (direct-weighting)	This alternative has relatively low bias and requires only the tree dbh and the distance from the tree to the boundary (or distance from the plot center to the tree and distance from the plot center to the boundary) to be measured.	This method is biased at all levels of inventory aggregation.
Area correction (tree centered)	This method provides unbiased estimates assuming the stand boundary is relatively straight within the tree circles.	This method is time-consuming in the field and requires precise locating of the stand boundary. In practice, estimates are likely to be imprecise.
Half plots	This method is relatively simple to implement.	Some bias remains and the resulting estimates have higher mean squared errors.
Grosenbaugh's method	This method provides unbiased estimates assuming the stand boundary is relatively straight within the tree circles.	This alternative requires the stand boundary and the boundary zone be delineated. The resulting estimates are somewhat imprecise.
Mirage method	This method provides unbiased estimates.	This method is somewhat cumbersome in the field and requires the stand boundary be located. Establishing two plots requires access to the adjacent stand.
Enlarged tree circle or Barett's method	This method provides unbiased estimates	In most cases, it is impractical to determine the tree areas near stand boundaries.
Fully mapped designs	This method provides unbiased estimates	Mapping the stand boundary may be difficult (impractical).
"Toss-back"	This method provides unbiased estimates and does not require measuring distances.	This method requires locating more plots and requires access to the area surrounding the stands. This method requires locating the boundary.

valid design and a large population (low probability of locating plots along the population boundary), none of the methods will add appreciable bias to the population estimates. In this discussion, the population is assumed to be large (>1,000 km^2) with strata (subpopulations) defined prior to sampling.

The advantages and disadvantages of each method are summarized in table 1.

Ignoring the Border

If trees are tallied regardless of whether they fall within the stand or not, the stand boundary is ignored (referred to as fuzzing by Hahn *et al.* (1995)). This results in bias and increased variance in stand and subpopulation estimates but no bias at the population level (ibid.), assuming all the points fall within the population of interest and all strata are sampled. All trees have the same probability of being sampled so the population estimates are unbiased, but some trees are attributed to the wrong stand and possibly stratum leading to biased stand and subpopulation estimates. This method leads to unbiased population estimates assuming all strata are sampled using a statistically valid design.

Moving the Plot (Substitution)

If a sample plot falls within a stand boundary zone, it can be moved away from the edge so that it falls entirely within the stand. Areas near the stand edge have a lower probability of being sampled and areas slightly farther from the edge have a higher probability of being sampled than the rest of the stand. The larger the amount of edge in a stand relative to area, the greater the resulting error (Shiver and Borders 1996).

The undersampling of conditions near the stand boundary leads to bias at all levels of inventory aggregation and incorrect estimates of the within- and between-stand variability.

Dropping the Plot

If part of the plot falls outside the stand, it can be dropped and the stand attributes estimated from a reduced number of plots. Ashley and Beers (1970) do not recommend restricting plots to the interior of the stand since the bias is more difficult to quantify and correct than the bias due to boundary plots.

Area Correction—Plot Centered (Direct-weighting)

If part of the sample plot falls outside of the stand, the portion within the stand can be sampled. The treatment of this partial plot depends on the type of plot. For fixed-area plots, the resulting data can be weighted by the partial plot area (called direct-weighting by Gregoire and Scott (1990)) although determining the plot area can be time-consuming. Variable radius plots are trickier. Beers (1966) (cited in Ashley and Beers (1970)) described direct-weighting where the distance from the point to the boundary is measured. The hypothetical circular plot area associated with each tree is calculated and centered at the sample point. The proportion of the hypothetical circular plot falling within the stand boundary is used as the inverse weight for the tree (see the area correction formula given in the next section). Either a lookup table or computer program is required to make this approach practical. In general, a more practical approach is to use the half-plot method discussed later.

Area Correction—Tree Centered

The area correction method (Iles' (1993) second approach, called FOLD by Hahn *et al.* (1995) and tree-concentric by Gregoire and Scott (1990)) compensates for the decreased selection probability of boundary trees by increasing their weight. For each tree, generate the tree circle with radius equal to the limiting distance of the tree, *r*, or the plot radius for fixed area plots and measure the shortest distance, *d*, from the tree to the stand boundary. The tree is weighted by the inverse of the proportion of the tree circle falling within the stand

$$weight = \frac{\pi r^2}{\pi r^2 - r^2(\theta - \frac{1}{2}\sin(\theta))} \quad \text{where} \quad \theta = 2 \cdot \cos^{-1}(\tfrac{d}{r}) \ .$$

This method requires that the distance from trees to the stand boundary be measured for trees close to the boundary. Alternatively, for stand boundaries that are relatively straight within the tree circle, the perpendicular distance and azimuth from the plot center to the boundary and the distance and azimuth from the plot center to the subject tree can be measured. The distance from the subject tree to the boundary can then be computed. The subsequent calculation of weights is best undertaken by a computer program.

This method assumes the stand boundary is relatively straight within the tree circles.

Half Plots

Rather than determine which portion of the plot falls within the stand and which falls outside, a half plot can be located. The original plot is bisected roughly parallel to the stand edge and the interior half is sampled. The plot results are then doubled to represent a whole plot. This procedure has some of the disadvantages of the relocating the plot method, namely that the edge trees have a slightly altered probability of being selected. However, these probabilities are not as distorted as in the relocating plot method.

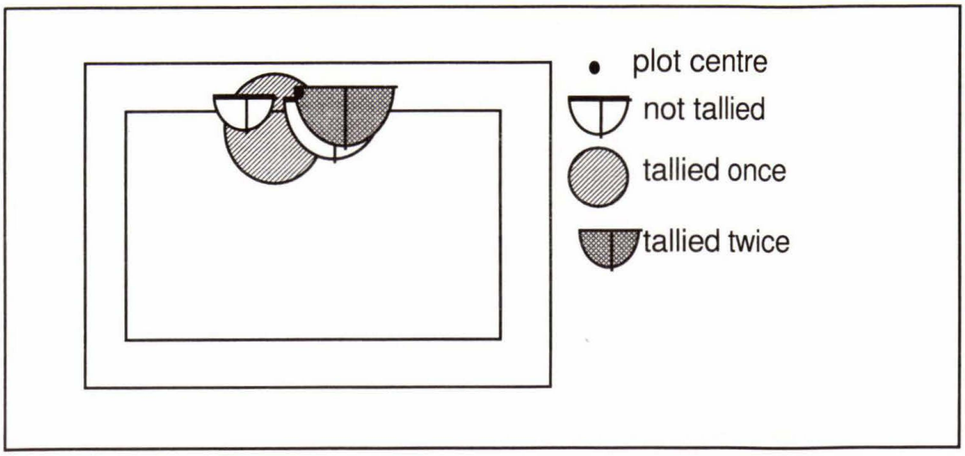


Figure 1.—*In Grosenbaugh's method, the tree circles for trees near the boundary zone are folded inward, parallel to the stand boundary. Trees are tallied the number of times the tree circle overlaps the plot center.*

This method requires that some sort of boundary zone be established. Within the boundary zone, half plots are used.

Grosenbaugh's Method (Grosenbaugh 1958)

The area within a fixed distance of the stand boundary is designated the boundary zone. The boundary zone should be a little wider than the radius of the maximum tree circle expected (Grosenbaugh 1958). Within the boundary zone, the tree circles are folded inward, parallel to the stand boundary. Trees within the boundary zone are tallied twice if their folded tree circles overlap the plot center. Trees in the stand's interior are tallied once. Trees within the fixed distance of two stand boundaries are folded twice, away from the boundary. These trees are tallied four times if the quarter circle includes the plot center (fig. 1).

For non-rectangular plots, this technique can be extended using fractional tree circles and sweeps. In practice, the angles should be limited to fractions with associated integer weights, i.e., sweeps of 180°, 120°, 90°, 72°, 60°, etc. leading to tree weights of 2, 3, 4, 5, and 6.

Both Ashley and Beers (1970) and Gregoire and Scott (1990) found that Grosenbaugh's method produced large variances due to the large weights associated with some boundary trees.

Mirage Method

Conceptually, the mirage method folds the plot along the stand boundary back into the stand. Trees within the folded area are tallied twice (fig. 2). In practice, the mirage method is implemented by establishing two plot centers, one inside the stand and the other the same distance from the stand boundary (measured perpendicular to the stand boundary) but outside the stand. For both plots, only the trees within the stand of interest are tallied and create one full plot (Shiver and Borders 1996). This method assumes a relatively straight boundary. This method can be extended to plots near stand corners by adding a second mirage plot along the second side of the corner and a third mirage plot by rotating the original point 180° along one of the sides (Gregoire 1982). Beers (1977) recommends the mirage method because it is unbiased and simple.

Enlarged Tree Circle or Barett's Method

In Barett's method, the tree circle associated with a tree is enlarged until the area of the tree circle within the stand of interest is equal to the original tree circle. Those trees whose enlarged tree circle includes the sample point are tallied (Barett 1964). For all suspected boundary trees, this method requires measurement of the tree diameter, shortest distance from tree to boundary, and distance from the plot center to the tree.

Fully Mapped Design

In fully mapped designs, the entire plot is mapped including stand boundaries. Trees are then assigned to a stand. This method is best suited when the plots are located randomly from the entire population rather than within specific stands. This procedure is recommended for the USDA Forest Service Forest Inventory and

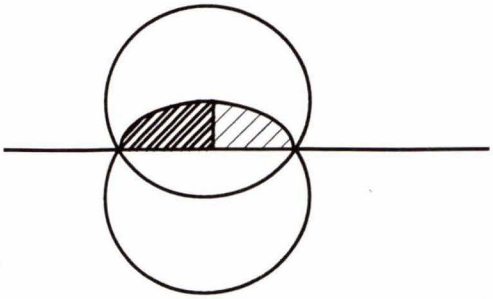


Figure 2.—*In the mirage method, tree circles are folded in along the stand boundary. Trees are tallied the number of times the tree circle overlaps the plot center.*

Analysis (FIA) program (Hahn *et al.* 1995) and the Forest Health Monitoring (FHM) program (Scott and Bechtold 1995).

"Toss-Back" Method

A variation on the fully mapped designs is the toss-back method (Haga and Maezawa 1959). In effect, plots are randomly located within the entire inventory area and only trees within the stands of interest are tallied. The stand of interest is embedded in a larger, superstand that contains all the tree circles in the stand of interest. Plots are randomly located within the superstand until the stand of interest contains the desired number of sample plots. All the plots in the superstand are sampled, but only trees falling within the stand of interest are tallied. The effective sample size is the number of plots whose centers fall within the stand of interest. The tallied trees from exterior plots (those plots whose center is outside the stand of interest) can be assigned to any of the interior plots. Iles (1993) recommends this system on theoretical grounds, and Stage (1993) prefers it over the fold methods. The possibility exists of trees being tallied but no plot centers falling within the stand of interest. This leads to the awkward case of a plot sample size of zero.

EXTERNAL PLOTS

When the sample unit consists of a cluster of points, a cluster with a center near the edge of the stand may include some points that fall outside the stand. These are referred to here as external plots. Some of the techniques used for boundary plots may be used, but substitution is the most common technique. If the only way of determining if a plot straddles two stands is by looking at the resulting data, Moisen *et al.* (1995) do not feel the plots need any special treatment.

No Substitution

Sampling plots with no substitution is equivalent to ignoring the border.

Dropping External Plots

The plot centers that fall outside the stand of interest can be dropped and the remaining points checked for boundary conditions. This results in biased estimates since, on average, fewer points are located near the boundaries.

Substitution

The current U.S. FIA substitution rule tends to move plots too far towards the interior of the stand so that the edge is underrepresented and the area slightly interior to the edge is overrepresented by sample points. In a simulation study using the U.S. FIA substitution rule, Moisen *et al.* (1995) found that if the tree variable of interest decreases by 100 percent from stand interior to edge and if 25 percent of the sample plots fall outside the boundary and have to be moved, the percent bias caused by not sampling all areas with equal probability would be approximately 3 percent. They recommend a new substitution rule that tends to substitute external plots with internal plots that are approximately the same distance from the boundary and are close to the cluster center. They also found little effect of a 10-percent uncertainty in boundary location relative to the boundary transition zone.

In a simulation study, Williams *et al.* (1996) compared substitution and no substitution using the USDA Forest Service Intermountain Forest Inventory and Analysis unit's five-point cluster design and substitution rules. The artificial populations were constructed to simulate various levels of edge effect between forest conditions. They found that using the no substitution alternative resulted in lower bias than using the substitution rules.

SIMULATION STUDY

A simulation study was undertaken to quantify the errors associated with the various alternatives presented earlier. Gregoire and Scott (1990) evaluated most of the alternatives using fixed-area plots. Therefore, this study concentrates on the two methods they didn't deal with—the half sweep and the toss-back methods—as well as ignoring the border and the tree-centered area correction.

Methods

The data set of Gregoire and Scott (1990) was used and consists of a rectangular forest area composed of a rectangular sapling stand and an adjacent rectangular sawlog stand. The 213- x 229-m area was stem mapped, and the data include dbh, height, and volume. A single variable-radius plot was randomly located within the forest stand. For this study, the plot cluster center x-coordinate was generated to lie between 50 and 163 m, while the y-coordinate was constrained to lie between -122 and 107 m. This ensured that a maximum of two forest conditions were encountered by any plot cluster, the sapling:sawlog boundary and the forest:non-forest boundaries that are parallel to the sapling:sawlog boundary. The Microsoft C++ random number generator was used to locate the cluster center. Only trees larger than 2 cm were tallied.

No correction, the tree centered area correction, half sweep, and toss-back methods were compared. Except for the toss-back method, only points whose center fell within the stand of interest were sampled. All plots were checked for boundary conditions and the relevant correction method applied where appropriate. An edge effect was noticeable within 15 to 30 m of the stand boundary

(Gregoire and Scott 1990), so a default boundary distance of 50 m was used. The half-sweep boundary distance was varied in a separate simulation. A range of BAF's from 1 to 10 m^2/ha was used.

Results

The results are given in table 2 and in figures 3 and 4. The stand values differ slightly from Gregoire and Scott (1990) because plot centers were not located within 50 m of the side boundaries. This results in a lower probability of encountering boundary plots. Not sampling the side boundaries yields slightly lower estimates because they contain more and larger trees.

The differences between the alternatives and any bias decrease with increasing BAF. This is due to the tree circles shrinking with increasing BAF and therefore a decreasing likelihood of encountering the boundary. This decrease in bias is accompanied by an increase in variance.

Using no correction resulted in an underestimate of the population attributes since some of the plots included the non-forested outer boundary. The sawlog basal area and volume were underestimated, and the sapling basal area and volume were overestimated. The variances of the population estimates were lower, in general, than the other techniques, but the stand estimate variances were higher.

The half sweep, in general, had lower bias than no correction at the stand level. In addition, the ranges and variances of the estimates were higher due to the reduced number of trees sampled and the increased weights. Except for the half sweep, the variances are very close.

DISCUSSION

Each technique for dealing with boundary plots has its strengths and weaknesses. Again, the magnitude of the boundary plot effect depends on the size and shape of the stands as well as the magnitude of the edge effect and the differences between the stands. In general, the unbiased techniques are more complex and time-consuming. Of the biased techniques, some are biased only at the stand and subpopulation level and unbiased at the population level (e.g., ignoring the border) assuming a statistically valid sampling design.

Since the differences between the techniques decrease with increasing BAF, another alternative is to increase the BAF near stand boundaries and minimize the need for any correction. Leaving such an important decision to the field crews may not be desirable.

Simplicity is extremely desirable so ignoring the border is a strong contender on that basis alone. Ignoring the border is biased at the stand level because some of the neighboring stand areas are included in the sample. This increases the estimate of the within-stand heterogeneity and decreases the estimate of the between-stand heterogeneity; some of the differences between stands are smoothed out. The seriousness of this smoothing depends on a number of factors including the magnitude of the edge effect and the percentage of plots that straddle two or more forest conditions.

All the other techniques require locating the stand boundary in the field. Although this may be difficult when the transition between stands is gradual, the importance of correcting boundary plots decreases for gradual boundaries. Thus, the bias caused by incorrectly locating the boundary in these conditions is minimal. Of greater concern may be the time field crews spend trying to locate a fuzzy boundary.

The half sweep is biased at all levels of inventory aggregation due to undersampling of the trees closest to the edge and oversampling of the trees a bit further from the edge. A lower BAF could be used for half sweeps to compensate for the increased variability, but the bias increases with lower BAF's. In the simulations undertaken here, the average bias for the basal area estimate was up to 2 percent at the stand level and 1.5 percent at the population level. However, the bias associated with a single sample point in the sapling stand ranged from 0 to 138 percent. For well-defined boundaries, both the area correction and toss-back methods provide good estimates. The area correction is a bit more time-consuming in the field, while the toss-back method requires locating more plots in the field.

RECOMMENDATIONS

A good compromise between practicality and accuracy appears to be the use of the area correction or toss-back methods when the boundary is distinct. For gradual boundaries or boundaries between similar types, the boundary should be ignored. In practice, the points should be located on photos and the type of correction for boundary plots selected, based on the photos. Rules for classifying a boundary as gradual or abrupt need to be established.

This combination of no correction and area correction and/or toss-back methods will lead to unbiased population estimates. Using no correction for gradual boundaries will lead to some minor bias at the stand and subpopulation levels.

The half sweep is not recommended except where there is no edge effect (e.g., edges due to recent disturbances) where it is unbiased. Otherwise an unknown amount of bias is present at all levels of compilation. Since unbiased

Table 2.—*The results of the 10,000 simulations are summarized by basal area factor. Ignoring the boundary (uncorrected - UC) is centered area correction (AC), half sweep (HS), and toss-back (TB) methods. The standard error (s.e.) is calculated as the square root of the s.e. of the simulations divided by the number of simulations.*

baf	Stand		Basal area (m²/ha)				Density (stems/ha)				Volume (m³/ha)				N
			UC	AC	HS	TB	UC	AC	HS	TB	UC	AC	HS	TB	
1	sapling	average	13.62	12.43	12.45	12.25	1,431	1,442	1,442	1,424	25.2	13.7	13.6	13.56	4,561
		s.e.	0.07	0.06	0.07		7.36	7.59	7.59		0.47	0.13	0.16		4,561
	sawlog	average	27.65	29.87	29.26	28.80	463	477	477	469	226.1	245.3	241	235.9	5,439
		s.e.	0.07	0.07	0.08		2.22	2.35	2.35		0.60	0.53	0.62		5,439
	total	average	21.25	21.91	21.59	21.25	904	917	917	905	134.4	139.7	137.3	134.5	10,000
		s.e.	0.09	0.10	0.10		10.85	11.00	11.00		1.08	1.19	1.18		10,000
2	sapling	average	13.31	12.43	12.50	12.31	1,434	1,441	1,441	1,428	22.2	13.8	13.8	13.64	4,561
		s.e.	0.08	0.07	0.10		9.70	9.90	9.90		0.43	0.17	0.22		4,561
	sawlog	average	28.33	29.94	29.43	29.17	469	480	480	474	231.5	245.6	241.7	238.7	5,439
		s.e.	0.08	0.08	0.10		2.95	3.06	3.06		0.68	0.65	0.84		5,439
	total	average	21.48	21.96	21.71	21.48	909	919	919	909	136	139.9	137.8	136	10,000
		s.e.	0.09	0.10	0.11		11.31	11.42	11.42		1.12	1.21	1.23		10,000
3	sapling	average	13.17	12.46	12.49	12.35	1,436	1,442	1,442	1,431	20.8	14	14	13.84	4,561
		s.e.	0.09	0.09	0.12		11.44	11.59	11.59		0.42	0.20	0.27		4,561
	sawlog	average	28.51	29.84	29.41	29.20	469	478	478	473	233.1	244.7	241.3	238.9	5,439
		s.e.	0.10	0.10	0.13		3.57	3.66	3.66		0.79	0.79	1.07		5,439
	total	average	21.51	21.91	21.69	21.51	910	918	918	910	136.3	139.5	137.6	136.3	10,000
		s.e.	0.10	0.11	0.12		11.71	11.80	11.80		1.16	1.23	1.28		10,000
4	sapling	average	12.98	12.43	12.50	12.33	1,433	1,439	1,439	1,428	19.4	13.9	14	13.84	4,561
		s.e.	0.10	0.10	0.14		12.94	13.09	13.09		0.40	0.23	0.32		4,561
	sawlog	average	28.62	29.76	29.44	29.17	468	476	476	472	234.1	244.1	241.6	238.8	5,439
		s.e.	0.11	0.11	0.16		4.13	4.23	4.23		0.88	0.90	1.26		5,439
	total	average	21.49	21.85	21.71	21.49	908	915	915	908	136.1	139.1	137.8	136.2	10,000
		s.e.	0.11	0.12	0.14		12.06	12.15	12.15		1.19	1.25	1.33		10,000
5	sapling	average	12.95	12.5	12.52	12.40	1,440	1,447	1,447	1,438	18.7	14	14.3	13.94	4,561
		s.e.	0.11	0.11	0.16		14.34	14.49	14.49		0.40	0.26	0.36		4,561
	sawlog	average	28.75	29.75	29.49	29.21	470	476	476	471	235.2	243.9	241.8	239.2	5,439
		s.e.	0.12	0.13	0.18		4.60	4.67	4.67		0.98	1.00	1.43		5,439
	total	average	21.55	21.88	21.75	21.54	913	919	919	912	136.4	139.1	138	136.5	10,000
		s.e.	0.11	0.12	0.15		12.48	12.57	12.57		1.22	1.27	1.38		10,000
7	sapling	average	12.97	12.63	12.70	12.54	1,453	1,459	1,464	1,451	17.9	14.4	14.8	14.34	4,561
		s.e.	0.13	0.13	0.19		17.06	17.19	24.68		0.40	0.30	0.44		4,561
	sawlog	average	28.85	29.64	29.45	29.21	471	476	482	473	236	242.9	241.3	239	5,439
		s.e.	0.14	0.15	0.21		5.43	5.51	7.79		1.17	1.20	1.73		5,439
	total	average	21.61	21.88	21.81	21.61	919	924	930	919	136.5	138.7	138.0	136.5	10,000
		s.e.	0.13	0.13	0.17		13.33	13.41	15.97		1.27	1.32	1.48		10,000
10	sapling	average	12.87	12.67	12.77	12.60	1,462	1,467	1,467	1,460	16.9	14.6	15.1	14.52	4,561
		s.e.	0.16	0.16	0.23		20.69	20.80	20.80		0.43	0.37	0.54		4,561
	sawlog	average	29.12	29.73	29.74	29.34	472	475	475	474	238.2	243.5	243.6	240.2	5,439
		s.e.	0.17	0.18	0.27		6.53	6.56	6.56		1.42	1.45	2.19		5,439
	total	average	21.71	21.95	22.00	21.71	923	928	928	924	137.3	139.1	139.4	137.3	10,000
		s.e.	0.14	0.15	0.20		14.5	14.6	14.6		1.36	1.40	1.66		10,000

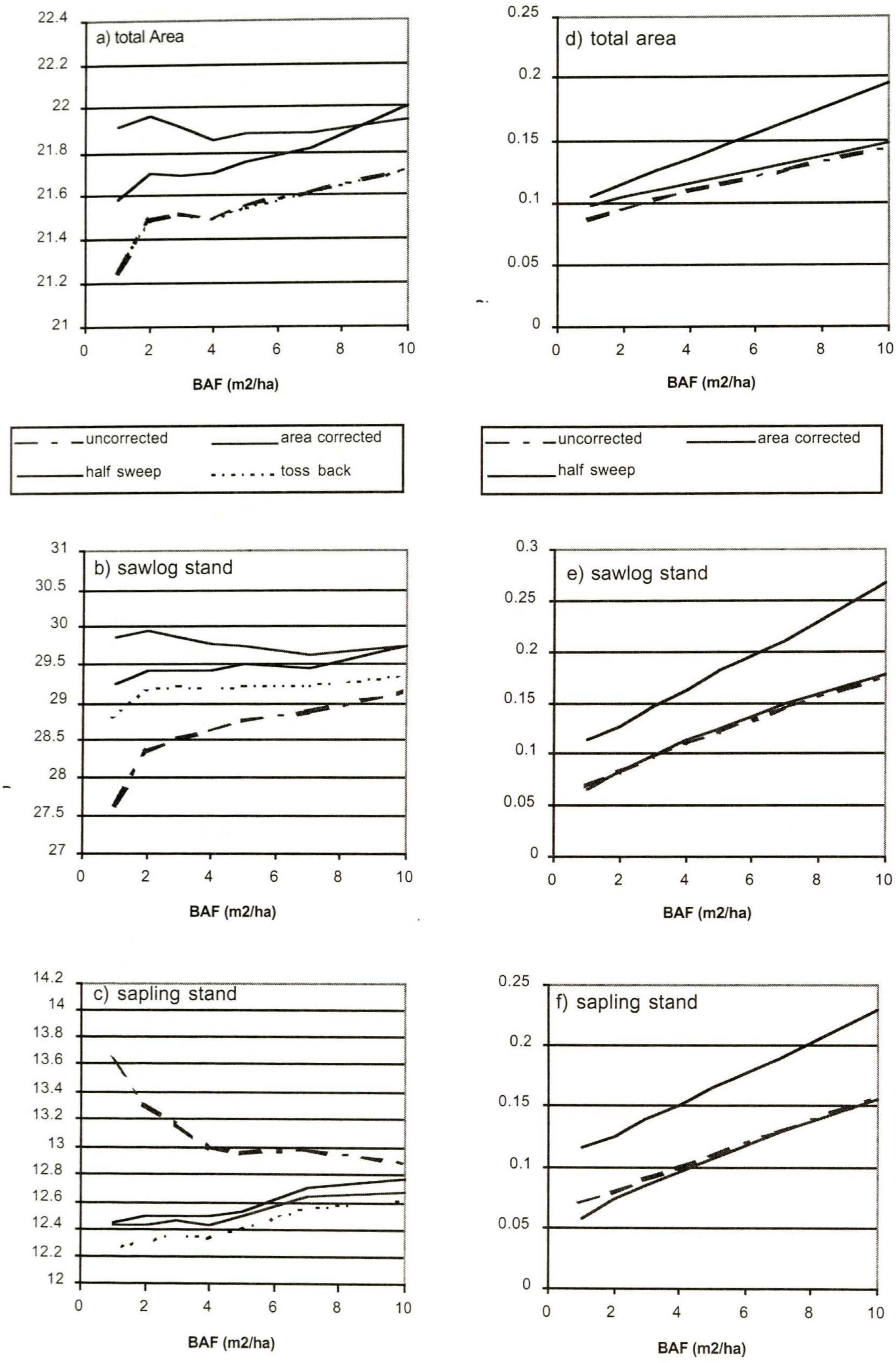


Figure 3.—*The relationship between the basal area estimates and the various correction methods is shown for various basal area factors (BAF) based on 10,000 simulations (data are from table 2).*

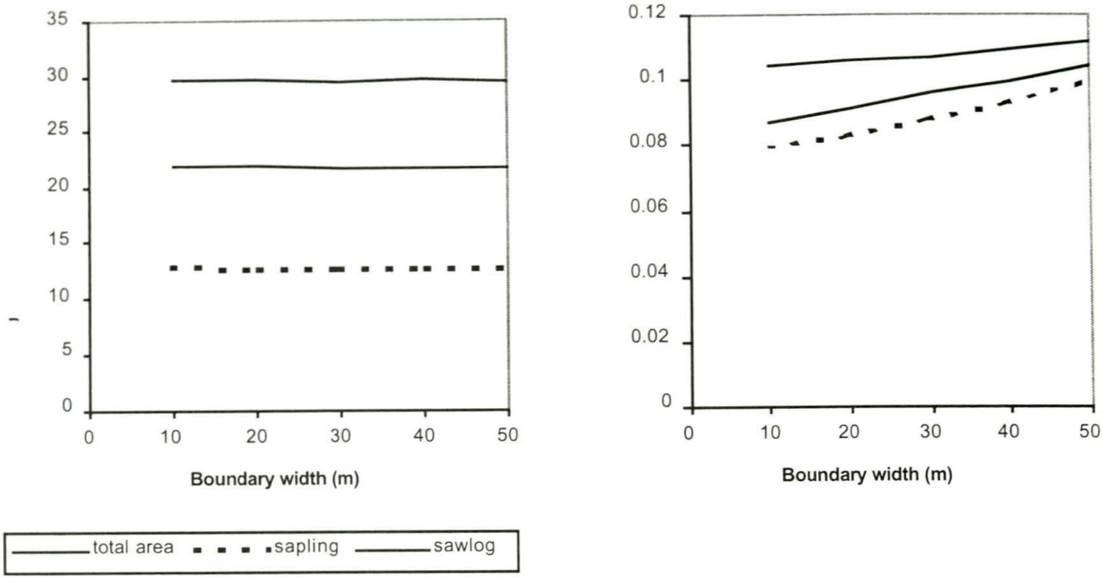


Figure 4.—*The relationship between the basal area estimates and boundary width for the half-sweep correction method is shown for a basal area factor of 2* m^2*/ha based on 10,000 simulations.*

methods are available and practical, this unquantified bias is unacceptable.

ACKNOWLEDGMENTS

This data set was made available by the Northeastern Research Station of the USDA Forest Service and by Chip Scott and Tim Gregoire. Their prior research and assistance and that of Kim Iles of Kim Iles & Associates are gratefully acknowledged. This study was initiated and funded by the Resources Inventory Branch of the British Columbia Ministry of Forests.

The following people reviewed this manuscript: Chip Scott, USDA Forest Service, Northeastern Research Station, and Steen Magnussen, Canadian Forest Service, Pacific Region.

LITERATURE CITED

Ashley, M.D.; Beers, T.W. 1970. Boundary-line overlap in horizontal point-sampling. Res. Bull. 865. West Lafayette, IN: Purdue University, Agricultural Experiment Station. 15 p.

Barett, J.P. 1964. Correction for edge effect bias in point sampling. Forest Science. 10: 52-55.

Beers, T.W. 1966. The direct correction for boundary-line slopover in horizontal point sampling. Res. Prog. Rep. 224. West Lafayette, IN: Purdue University, Agricultural Experiment Station.

Beers, T.W. 1977. Practical correction of boundary overlap. Southern Journal of Applied Forestry. 1: 16-18.

Birdsey, R.Q. 1995. A brief history of the "straddler plot" debates". Forest Science Monograph. 31: 7-11.

Fortin, M.-J. 1977. Effects of data types on vegetation boundary delineation. Canadian Journal of Forest Research. 27: 1851-1858.

Gregoire, T.G. 1982. The unbiasedness of the mirage correction procedure for boundary overlap. Forest Science Monograph. 31: 504-508.

Gregoire, T.G.; Scott, C.T. 1990. Sampling at the stand boundary: a comparison of the statistical performance among eight methods. In: Research in forest inventory, monitoring, and growth and yield: IUFRO World Congress; 1990 August 5-11; Montreal, Canada. Publ. FWS-3-90. Blacksburg, VA: Virginia Polytechnic Institute and State University: 78-85.

Grosenbaugh, L.R. 1958. Point-sampling and line-sampling: probability theory, geometric implications, synthesis. Occas. Pap. 160. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 33 p.

Haga, T.; Maezawa, K. 1959. Bias due to the edge effect in using the Bitterlich method. Forest Science. 5: 370-376.

Hahn, J.T.; MacLean, C.D.; Arner, S.L.; Bechtold, W.A. 1995. Procedures to handle inventory cluster plots that straddle two or more conditions. Forest Science Monograph. 31: 12-25.

Iles, K. 1993. Edge effect in forest sampling: the "lower back pain" of field work: a background paper for the sampling sub-committee of the BC Inventory Design. Nanaimo, BC: Kim Iles & Associates Ltd. 17 p.

Moisen, G.G.; Stage, A.R.; Born, J.D. 1995. Point sampling with disjunct support near population boundaries. Forest Science Monograph. 31: 62-82.

Scott, C.T.; Bechtold, W.A. 1995. Techniques and computations for mapping plot clusters that straddle stand boundaries. Forest Science Monograph. 31: 46-61.

Shiver, B.D.; Borders, B.E. 1996. Sampling techniques for forest resource inventory. New York, NY: John Wiley and Sons, Inc. 356 p.

Stage, A.R. 1993. How to sample within stands. In: Lund, H.G.; Landis, E.; Atterbury, R., eds. Stand inventory technologies 92: proceedings of the stand inventory technologies: an international multiple resource conference. Bethesda, MD: American Society for Photogrammetry and Remote Sensing: 85-91.

Williams, M.S.; Schreuder, H.T.; Reich, R.M. 1996. The extent of bias caused by substituting points in forest survey: a simulation study. Res. Pap. RM-327. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 7 p.

Guided Transect Sampling—A New Design Combining Prior Information and Field Surveying

Anna Ringvall, Göran Ståhl, and Tomas Lämås

Abstract.—Guided transect sampling is a two-stage sampling design in which prior information is used to guide the field survey in the second stage. In the first stage, broad strips are randomly selected and divided into grid-cells. For each cell a covariate value is estimated from remote sensing data, for example. The covariate is the basis for subsampling of a transect through the broad strip. The general idea of guided transect sampling can be combined with different transect-based field inventory methods. This paper describes guided transect sampling and provides some results from a theoretical evaluation.

Sparse populations, for which no list exists, generally pose substantial problems in sampling. This is the case in forestry, such as when studying elements of importance for biodiversity or a population of some indicator species. The plot-based methods generally used for timber cruising tend to give imprecise estimates for rare objects since only a small area is covered and a relatively long time is spent traveling between plots. For sparse objects, transect-based methods like strip surveying should be more cost-efficient because a larger area is covered (Lämås and Fries 1995). Line transect sampling (e.g., Buckland *et al.* 1993) has mainly been used for assessing wildlife populations, but is also a good alternative for sparse inanimate objects. Lately, adaptive cluster sampling (Thompson 1990, Roesch 1993) has been proposed as an efficient method for sparse and aggregated populations. Still, inventories can be expensive and/or provide imprecise results.

Prior information about the population studied can be used in many ways to enhance the precision of estimates. Techniques such as stratification and probability proportional to size (PPS) use the information for selecting the samples, while ratio and regression estimators, for example, use the information for estimation purposes.

This paper concerns a newly developed method (Ståhl *et al.* 1997) thought to increase the efficiency in transect-based sampling methods when the object of interest is sparse and geographically scattered. The method, guided transect sampling (GTS), is a two-stage probability sampling design. In the first stage, wide strips are laid out, and in the second stage, the subsampling of a transect inside the wide strip is guided by prior information, as in the form of remote sensing data. The aim of this paper is to give a general description of GTS and to provide some preliminary results regarding its efficiency.

THE METHOD

An overview of the method is provided in figure 1. In the target area delineated (left in fig. 1), broad strips are first randomly laid out. The strips are partitioned into grid-cells of some suitable size, e.g., 20 x 20 m. For each such cell, a covariate value is assessed prior to sampling. For example, the covariate could be the estimated volume of deciduous trees if the population studied is known to prefer deciduous trees to conifers in mixed stands. Such volume estimates can be obtained from satellite imagery or aerial photos (e.g., Tomppo 1986, Nilsson 1997).

Secondly, grid-cells are subsampled along a survey line across each first-stage strip (right in fig. 1). The subsampling is based on the covariate values in each grid-cell. The general idea of GTS can be combined with different kinds of transect-based inventory methods, such as strip surveying, line transect sampling, and adaptive cluster sampling with a strip as the initial unit. However, in the theoretical description of the method in this article, GTS is supposed to be combined with a strip survey

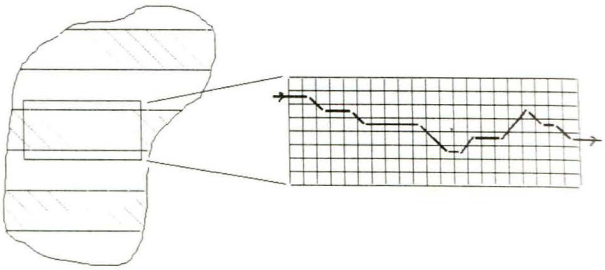


Figure 1.—*The general outline of GTS. A first-stage sampling of wide strips (left) is followed by a second-stage guided subsampling of a transect within each strip (right).*

Graduate Research Assistant, Professor in Forest Inventory, and Assistant Professor in Forest Management Planning, respectively, Department of Forest Resource Management and Geomatics, Swedish University of Agricultural Sciences Umeå, Sweden.

approximated as a survey of the entire grid-cells selected. In reality, the method also relies on the use of GPS, differential in real time, to guide the survey or along the predetermined transects.

Strategies for Guidance

Different strategies can be used for selecting the second-stage transect. Some straightforward possibilities are:

1. Random walk with transitions allowed only to neighboring cells in the next grid-cell column (fig. 2a). The decision about which cell to enter is made PPS to the neighboring cells' covariate values.

2. As strategy 1, but allowing the surveyor to step from a particular cell to any of the grid-cells in front. The second-stage transect will no longer be connected (fig. 2b).

3. Random simulation of entire transects through the first-stage strip without considering the covariate data. Transitions are allowed only to neighboring cells in the next grid-cell column as in strategy 1. However, here, there is an equal probability of transition to each of the neighboring cells since no covariate data are considered at this moment. Many transects are simulated, and for each transect the sum of covariate values in all grid-cells passed by that transect (the *Q*-value) is calculated. Finally, one transect is selected PPS to this sum of covariates (fig. 2c).

The choice of subsampling strategy will affect the simplicity of applying the method in the field as well as the precision of GTS. Theoretically, strategy 2 should be most efficient since cells with large covariate values always have a high probability of being selected. The simplicity of surveying along a continuous transect will, however, be lost. Strategy 1 gives connected transects, but it might be inefficient because interesting areas sometimes will have a very low probability of being selected. Strategy 3 could be regarded as a compromise between strategy 1 and 2. It will lead to connected transects, and the inefficiency that might occur with strategy 1 is reduced if enough transects are simulated.

ESTIMATION

Attention will first be given to conditional estimation within a primary unit. The general principle is to use the Horvitz-Thompson (HT) estimator (e.g., Cochran 1977), by which a first-stage strip total, Y_i, is unbiasedly estimated as:

$$\hat{Y}_i = \sum_{j=1}^{m_i} \frac{y_{ij}}{\pi_{ij}} \qquad (1)$$

Here, y_{ij} is the characteristic of interest in the *j*th grid-cell sampled in first-stage strip *i*, (π_{ij} the probability of including this grid-cell in the sample, and m_i the number of grid-cells sampled in first-stage strip *i*.

To arrive at an estimator for the entire area under study, the method for selecting the first-stage strips must be considered. If this selection is made by simple random sampling, assuming all primary units to have equal size, an estimator of the population total, $\hat{Y}_{tot}$, is obtained as:

$$\hat{Y}_{tot} = \frac{1}{n}\frac{A}{a}\sum_{i=1}^{n}\hat{Y}_i \qquad (2)$$

with *A* being the total area of the compartment, *a* the area of a first-stage strip, *n* the number of first-stage strips sampled, and $\hat{Y}_i$ the estimator of the population (sub-)total within first-stage strip *i*.

Inclusion Probabilities

The probabilities of inclusion of grid-cells will vary depending on what strategy is used for guiding the subsampling. Below, the derivation of inclusion probabilities will be described for the three cases previously discussed. For simplicity, a rectangular forest with *m* columns is assumed. All first-stage strips are assumed to have a width of *r* rows and to extend across the entire area under study, parallel with two of the sides in the rectangle. All derivations are made within a selected first-stage strip. In this section, notations for grid-cells are two-dimensional, indicating the row and the column.

Strategy 1: The grid-cell to enter the strip is selected PPS among all possible cells in column 1. The probability of inclusion of the grid-cell in row *j*, column 1, is then:

$$\pi_{j1} = \frac{x_{j1}}{\sum_{l=1}^{r} x_{l1}} \qquad (3)$$

with x_{j1} being the covariate value of the *j*th cell in the first column and *r* the number of rows in the first-stage strip. Note that all the *x*-values must be larger than zero for the strategy to be theoretically sound. If a grid-cell's covariate is zero initially, some small number must be added before the formula is applied.

Looking next at the probabilities of inclusion for grid-cells in column 2, these depend on the probabilities of inclusion of cells in the first column. The following recursive formula can be used from column 2 onwards, to the end of the strip:

$$\pi_{jk} = \sum_{l \in \Omega_{k-1}} \left(\pi_{l(k-1)} \cdot \frac{x_{jk}}{\sum_{s \in \psi_l} x_{sk}} \right) \qquad (4)$$

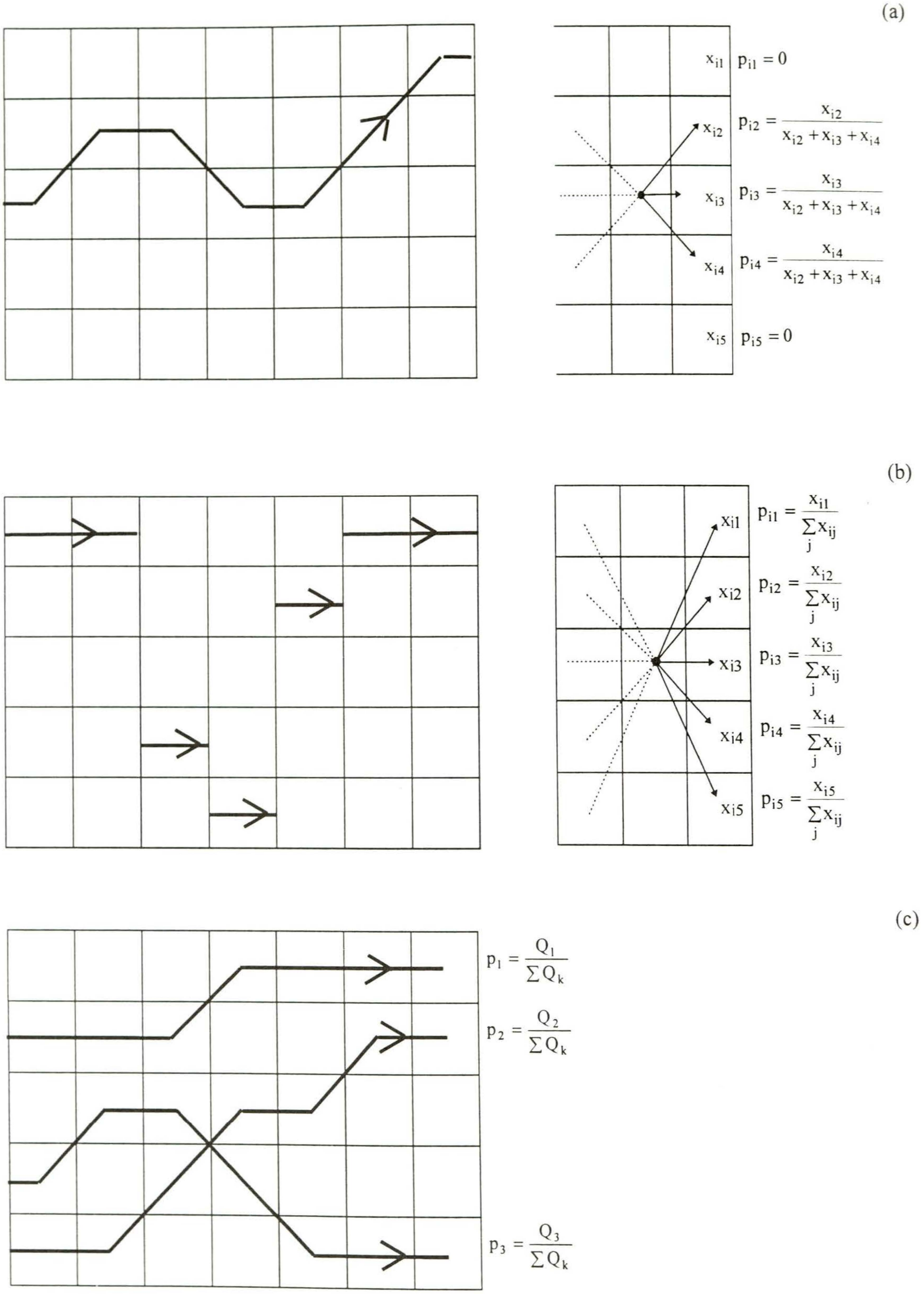

(a)
x_{i1} $p_{i1} = 0$
x_{i2} $p_{i2} = \frac{x_{i2}}{x_{i2} + x_{i3} + x_{i4}}$
x_{i3} $p_{i3} = \frac{x_{i3}}{x_{i2} + x_{i3} + x_{i4}}$
x_{i4} $p_{i4} = \frac{x_{i4}}{x_{i2} + x_{i3} + x_{i4}}$
x_{i5} $p_{i5} = 0$
(b)
x_{i1} $p_{i1} = \frac{x_{i1}}{\sum_j x_{ij}}$
x_{i2} $p_{i2} = \frac{x_{i2}}{\sum_j x_{ij}}$
x_{i3} $p_{i3} = \frac{x_{i3}}{\sum_j x_{ij}}$
x_{i4} $p_{i4} = \frac{x_{i4}}{\sum_j x_{ij}}$
x_{i5} $p_{i5} = \frac{x_{i5}}{\sum_j x_{ij}}$
(c)
$p_1 = \frac{Q_1}{\sum Q_k}$
$p_2 = \frac{Q_2}{\sum Q_k}$
$p_3 = \frac{Q_3}{\sum Q_k}$

Figure 2.—*Different strategies for guiding the subsampling. In (a) transition is allowed only to neighboring cells, in (b) transition is allowed to any onward cell, and in (c) entire transects are simulated. In (a) and (b), the probabilities of transition to the onward cells (the p-values) are determined from the covariate values (x-values) in the cells in the onward column, here denoted i. In (c), an entire transect is selected PPS to the sum (Q-values) of covariates in grid-cells passed by the transect.*

In this formula, Ω_{k-1} is the set of neighbor cells in the previous column (k-1) of the grid-cell in row j, column k. The set usually consists of three cells, although at the upper and lower boundary of a first-stage strip, it consists of only two cells. Moreover, Ψ_l is the set of neighbors in front of the grid-cell in row l, column k-1, providing the possible transitions from that particular grid-cell onwards. Generally, this set also consists of three cells except at the borders of the first-stage strip.

Strategy 2: In this case the probability of inclusion of a grid-cell depends only on the covariate values of the grid-cells in that particular column. The probabilities are always given by:

$$\pi_{jk} = \frac{x_{jk}}{\sum_{l=1}^{r} x_{lk}} \tag{5}$$

As in strategy 1, all x-values must be larger than zero; otherwise, a small number must be added to all the x-values before applying the formula.

Strategy 3: Here, entire transects are first simulated without considering the covariate information. Next, covariate data for grid-cells passed by the transect are summed, resulting in a value Q_l for the entire transect l. Out of the large number of transects simulated, one is selected PPS to the Q-values. The probability of inclusion of a particular grid-cell (conditioned on the realization of transects) is:

$$\pi_{jk} = \frac{\sum_{s \in S} Q_s}{\sum_{l \in L} Q_l} \tag{6}$$

Here, S is the set of transects that pass the grid-cell in row j, column k, and L is the set of all transects simulated. For this formula to be theoretically sound, every grid-cell must be passed by at least one transect.

Precision of Estimates

The precision, in terms of the variance, can be derived from the general formula for conditional variances (e.g., Cochran 1977):

$$Var(\hat{Y}_{tot}) = Var\left[E(\hat{Y}_{tot} | S)\right] + E\left[Var(\hat{Y}_{tot} | S)\right] \tag{7}$$

where $\hat{Y}_{tot}$ is the estimator of the population total and S the set of first-stage strips in the sample.

Under the assumption of simple random sampling, without replacement, of n first-stage strips among N possible, formula (7) can be further elaborated to:

$$Var(\hat{Y}_{tot}) = \left(\frac{A}{a}\right)^2 \frac{1}{nN}\left[\left(\frac{N-n}{N-1}\right)\sum_{i=1}^{N}(Y_i - \bar{Y})^2 + \sum_{i=1}^{N} Var(\hat{Y}_i)\right] \tag{8}$$

Here, N is the total number of first-stage strips, and the rightmost variance terms are those from the second stage guided transect inventories. These are calculated with the formula for the variance of an HT estimator (e.g., Cochran 1977):

$$Var(\hat{Y}_i) = \sum_{j=1}^{M_i} \frac{(1-\pi_j)}{\pi_j} y_j^2 + \sum_{j=1}^{M_i} \sum_{k \neq j}^{M_i} \frac{(\pi_{jk} - \pi_j \pi_k)}{\pi_j \pi_k} y_j y_k \tag{9}$$

where π_j and π_k now is the inclusion probability of grid-cell j and k, respectively, π_{jk} the joint inclusion probability of the cells j and k, M_i the number of grid-cells in first-stage unit i, and y_j the quantity of interest in the jth cell. The joint probabilities of inclusion are calculated according to the same principles that are used for calculating the individual probabilities of inclusion. Focus is set on one grid-cell at the time, and the probability that this particular cell occurs in the sample simultaneously with another is calculated.

COMPARISON OF GTS VERSUS STRIP SURVEYING

To give an indication of the efficiency of GTS and the performance of the different strategies for subsampling, comparisons were made with a traditional strip survey in two fictitious "forests." The example was designed to resemble inventories of some scarce species in restricted areas of coniferous forests with patches of deciduous trees. Many red-listed species depend on deciduous trees (Berg *et al.* 1993), and the covariate was considered to be the volume of deciduous trees assessed from aerial photos or satellite imagery. The parameter of interest could then be the population total of some quantity, such as the total biomass of the species of interest. The two forests had different levels of scarcity of the covariate and the species of interest.

Simulation of Fictitious Forests

The two forests (Forest I and Forest II) consisted of rectangular matrices of 50 by 25 grid-cells. The quantity of the covariate and variable of interest was simulated in four steps:

1. First, each grid-cell was independently assigned either a covariate value equal to zero, or a covariate value greater than zero. The proportion of grid-cells with a nonzero covariate was 0.3 in Forest I and 0.1 in Forest II.
2. For grid-cells with a covariate value greater than zero, the value was independently simulated from a normal distribution with mean 50 and standard deviation 35, truncated to prevent values below zero.

3. The probability of occurrence of the species of interest in grid-cell j, P_j, was determined with the following (slightly modified) logistic model:

$$P_j = \frac{\exp(\alpha + \beta \cdot x_j) + P^*}{1 + \exp(\alpha + \beta \cdot x_j)} \tag{10}$$

where x_j is the value of the covariate in grid-cell j, P^* the probability of occurrence of the species of interest when the covariate value is zero (0.03 in Forest I and 0.01 in Forest II), α and β parameters chosen to make P_j close to P^* when the value of the covariate is close to zero and P_j near 1 when the covariate is above 100 ($\alpha=-5$, $\beta=0.01$). A uniform random number was generated, and if the random number was smaller than P_j, the species of interest occurred in grid-cell j.

4. For cells with occurrence of the species of interest, the biomass of the species, y_j,, was modeled as:

$$y_j = \gamma \cdot x_j + \varepsilon_j \cdot x_j + \delta_j \tag{11}$$

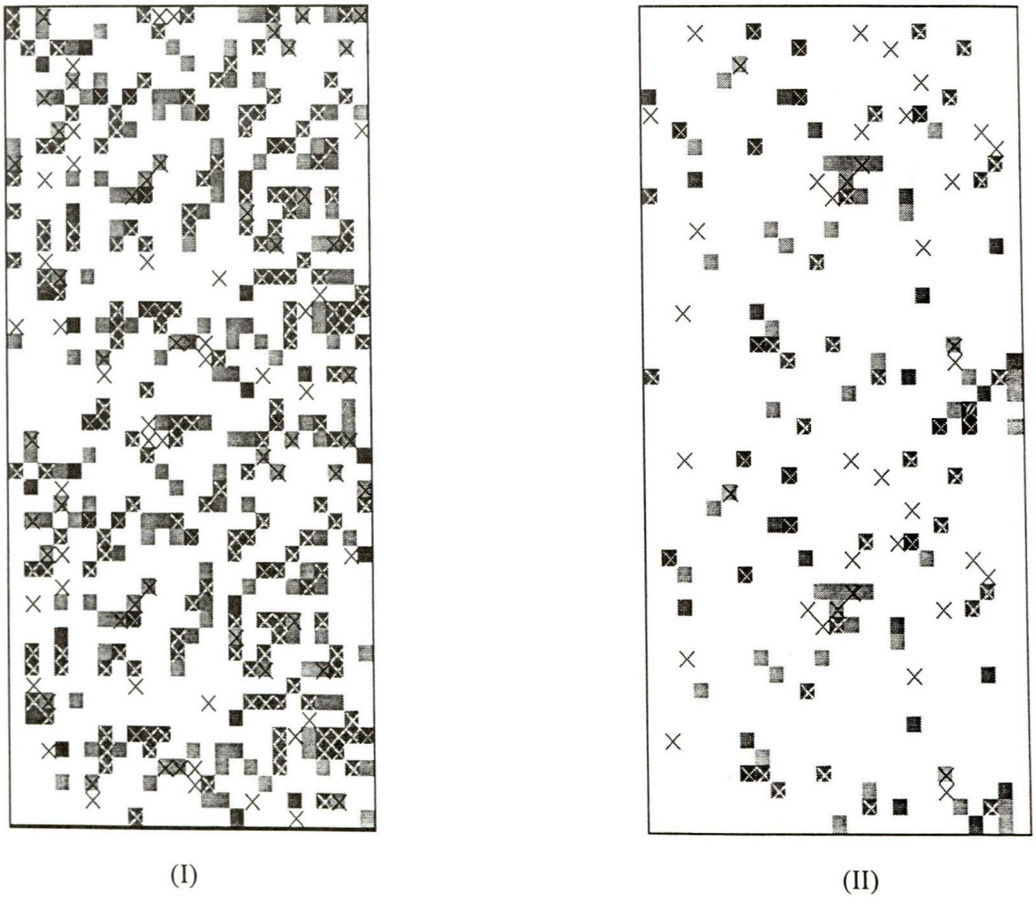
where x_j is the value of the covariate in grid-cell j, γ a scaling constant ($\gamma=0.2$), ε_j a normally distributed random variable ($\mu=0$, $\sigma^2=0.02$), and δ_j a log-normally distributed random variable ($\mu=0$, $\sigma^2=1$), added to assign a substantial random component to grid-cells where the value of the covariate was low.

Finally, a small constant was added to all grid-cells to give grid-cells with a covariate equal to zero an inclusion probability larger than zero.

Both forests were produced in 10 replicates to avoid conclusions based on extreme patterns in single outcomes. Examples of the two forest types are shown in figure 3. The mean values of the population total in the 10 replicates were 3164.3 (Forest I) and 1122.8 (Forest II), respectively.

Inventory Design

In this theoretical setup, it was assumed that entire grid-cells were selected and that the width of the strip or transect was equal to the size of the grid-cells so that


(I)

(II)

Figure 3.—*Examples of the two simulated forests used in the study. Colored squares indicate grid-cells with a nonzero covariate. The darker the color, the higher the value of the covariate. The crosses indicate presence of the species of interest in a grid-cell.*

selected grid-cells were entirely surveyed. Considering this setup and the small forests used, there is a finite number of possible samples of strips and primary units that makes it possible to analytically calculate the estimators' true variances. No simulations are thus involved in the comparison of the methods' efficiency, only in generating the forests.

For GTS, variances were calculated for a design in which one first-stage strip was selected with simple random sampling. Within the first-stage strip, a transect was subsampled using each of the three strategies for guidance earlier described. For each possible first-stage strip, inclusion probabilities and joint inclusion probabilities were calculated for each grid-cell and each pair of grid-cells using formulas (3-6). Then, the variance of the estimator was calculated using formulas (8-9). Two different widths for the first-stage strips were tested, 5 and 10 rows of grid-cells, respectively. For the traditional strip survey, variances were calculated for a design where one strip was selected with simple random sampling. The width of the strip was one grid-cell, and thus equal numbers of grid-cells were sampled with both GTS and the standard strip survey. The variance for the estimator was calculated as:

$$Var(\hat{Y}_{tot}) = \left(\frac{A}{a_{ST}}\right)^2 \frac{1}{nN_{ST}} \frac{N_{ST}-n}{N_{ST}-1} \sum_{i=1}^{N_{ST}} \left(Y_{i(ST)} - \overline{Y}_{ST}\right)^2 \qquad (12)$$

where $\hat{Y}_{tot}$ is the estimator of the population total, A the area of the forest, a_{ST} the area of the strip, N_{ST} the number of possible strips, n the number of strips sampled, $Y_{i(ST)}$ the total in the ith strip, and $\overline{Y}_{ST}$ the average of strip totals.

Results

Results are shown in figure 4 as:

$$R = \frac{Var_{GTS}(\hat{Y}_{tot})}{Var_{ST}(\hat{Y}_{tot})} \qquad (13)$$

where Var_{GTS} and Var_{ST} are the mean values of variances obtained with GTS and the standard strip survey, respectively, in each of the 10 replicates of the two forest types.

As suspected, strategy 2 was always most efficient in terms of statistical efficiency. Since this strategy leads to disconnected transects and, consequently, time spent walking without observing eventual objects, the strategy will probably be less cost-efficient. A possible improvement would be to allow transitions between rows only each 5th or 10th column. For the two strategies leading to connected transects, strategy 3 seems to be the most reliable. The risk of poor efficiency using strategy 1 is especially evident using a first-stage strip with a width of 10 rows in Forest I. An improvement of strategy 1 would be to look several columns ahead, not just one, when

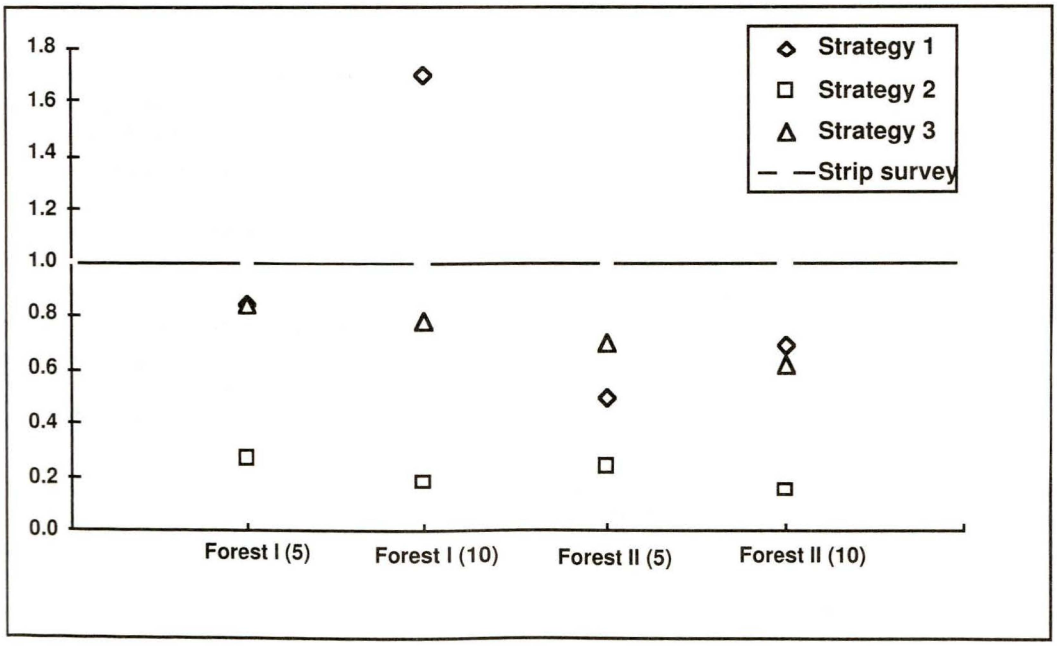


Figure 4.—*Comparison of guided transect sampling versus a standard strip survey, shown as the ratio between the variance of guided transect sampling and the variance of the strip survey. Results are shown for three different strategies of subsampling in two different forest types (I-II) and with two different widths of first-stage strips (5 and 10 rows of grid-cells).*

determining which transition to make. Both strategy 1 and strategy 3 seem to be relatively more efficient when the covariate and object of interest is less common.

DISCUSSION

This small study showed that GTS could improve the efficiency in a traditional strip survey for sampling sparse populations. However, the efficiency depends on the relationship between the variable of interest and the covariate, and when this relationship is expected to be poor, the method's potential is limited. Moreover, no costs were considered in this study, and although the same number of grid-cells was sampled using both GTS and strip surveying, the cost of performing GTS can generally be expected to be higher. Also, the availability and precision of the GPS guidance must be considered since deviations from the selected transects will affect the precision of the method.

The basic method presented can be developed and adjusted in many ways. The three strategies used for the second-stage guidance in this study are just some straightforward alternatives from a larger number of possibilities. Some improvements to the strategies developed for this study have already been discussed. Another more complicated, yet interesting, alternative would be to find an optimal strategy considering costs for entering different cells, and then for a given total cost, search for the transect giving the lowest variance, using some kind of optimizing routine.

In this study, GTS was combined with a strip survey, approximated as a survey of entire grid-cells selected. In practice, it would be desirable to survey strips along continuous lines. Then, only parts of grid-cells will be surveyed when changing rows in the grid-cell system, and inclusion probabilities will also have to be modified. Other interesting possibilities would be to combine GTS with line transect sampling or adaptive cluster sampling. This, however, would require further theoretical development. For objects or species that for some reason are difficult to survey using line-based methods, GTS could be combined with a sparse sample plot inventory.

Another possible way to improve the method would be to use the covariate data not only for selecting transects, but also for selecting the entire first-stage strips with PPS, and for estimation purposes.

ACKNOWLEDGMENT

The following people reviewed this manuscript: Jeffrey H. Gove, USDA Forest Service, Northeastern Research Station. Durham, NH, USA, and Sören Holm, Swedish University of Agricultural Sciences. Umeå, Sweden.

LITERATURE CITED

Berg, Å.; Ehnström, B.; Gustavsson, L.; Hallingbäck, T.; Jonsell, M.; Weslien, J. 1994. Threatened plant, animal and fungus species in Swedish forests: distribution and habitat associations. Conservation Biology. 8: 718-731.

Buckland, S.T.; Anderson, D.R.; Burnham, K.P.; Laake, J.L. 1993. Distance sampling. Estimating abundance of biological populations. London: Chapman & Hall. 446 p.

Cochran, W.G. 1977. Sampling techniques, 3d ed. New York, NY: John Wiley & Sons. 428 p.

Lämås, T.; Fries, C. 1995. An integrated forest inventory in a managed north Swedish forest landscape for estimating growing stock and coarse woody debris. In: Köhl, M.; Bachmann, P.; Brassel, P.; Preto, G., eds. Proceedings, The Monte Verità conference on forest survey designs. 1994 May 2-7, Monte Verità, Switzerland. Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf.

Nilsson, M. 1997. Estimation of forest variables using satellite image data and airborne lidar. Silvestria 17. Umeå, Sweden: Swedish University of Agricultural Sciences. Ph.D. dissertation.

Roesch, F.A., Jr. 1993. Adaptive cluster sampling for forest inventories. Forest Science. 39: 655-669.

Ståhl, G.; Ringvall, A.; Lämås, T. 1997. Guided transect sampling. An outline of the principle. Working document 19. Umeå, Sweden: Department of Forest Resource Management and Geomatics. SLU. 9 p.

Thompson, S.K. 1990. Adaptive cluster sampling. Journal of American Statistical Association. 85: 1050-1059

Tomppo, E. 1986. Stand delineation and estimation of stand variables by means of satellite images. Research Notes 19. Helsinki, Finland: University of Helsinki, Department of Forest Mensuration and Management.

Pseudo-CFI for Industrial Forest Inventories

Francis A. Roesch

Abstract.—Corporate inventory systems have historically had a greater spatial and temporal intensity than is common in the public sector. For many corporations, these inventory systems might be described as dynamic in that current estimates rely on a small amount of recent data and a large amount of information resulting from the imputation of older data that have been subjected to various growth and mortality models. Usually the "best available" models are used for this purpose, with little attention paid to any population dynamics that may have occurred since development of the models. This paper gives the theory and an example application of a family of sample designs that possess continuous forest inventory (CFI) attributes. This family of Pseudo-CFI sample designs was devised to facilitate the incorporation of a continuous monitoring and calibration mechanism for the imputed data.

It is important to industrial forest enterprises to know what is and what will be on the ground (by a wide array of measures) at any given point in time. For this reason, corporate inventory systems have historically had a greater spatial and temporal intensity than is common in the public sector. For many corporations, these systems might be described as dynamic in that current estimates rely on a small amount of recent data and a large amount of imputed data values based on older data that have been subjected to a growth model. Usually the "best available" growth and yield models are used for this purpose, with little attention paid to the appropriateness of the models for specific applications. Unfortunately, industrial forest populations are themselves quite dynamic and ever more frequently prove to be quite different from any of those upon which existing models were built. Furthermore, we can expect this trend to continue indefinitely. Therefore, it would be prudent to incorporate a continuous monitoring and calibration mechanism into the inventory system in order to provide the ability to adapt to changing conditions and populations. This paper presents a family of sample designs, which lie between periodic inventories and continuous forest inventories with respect to the variance and cost scales. An example application is also included. Because the designs are obtained by relaxing the requirements of continuous forest inventory, these designs might be dubbed Pseudo-CFI.

Much work has been devoted to studying the continuum along which different methods of scientific inquiry could be positioned with respect to the level of control over responses (Basu 1980; Cochran 1965; Cochran and Rubin 1974; Rubin 1973a, 1973b, 1974, 1976a, 1976b, 1978, 1979, 1980, 1986; Wickramarante and Holford 1987; Wold 1956). The subject was briefly introduced into the forestry literature in a discussion of forest response studies by Green and Roesch (1993). A major premise of this paper is that there is a point at which observational forest inventory data can begin to overrule the results of controlled growth and yield experiments. Here, we show how one might exploit that premise in the design of a dynamic inventory system.

Arguments for strict experimental control in growth and yield estimation and for the use of the less controlled continuous forest inventory (CFI) approach both rely on a very basic truth about random variables. That truth is that the variance of the difference between two random variables (A and B) is:

$$Var(A-B) = Var(A) + Var(B) - 2Cov(A,B)$$

If we let A equal time 2 volume and B equal time 1 volume, we see that A-B equals volume growth. Both controlled experiments and CFI plots attempt to maximize the third term on the right-hand side (*rhs*) of the equation, $2Cov(A,B)$, by measuring time 1 and time 2 volumes on the same population elements. This results in a decrease, of course, on the left-hand side (*lhs*) of the equation. Controlled experiments go one step further by also reducing the first two terms on the *rhs*. This is accomplished by controlling the population elements entering the experiment to a particular subset of the population of interest. That is, the point of an experiment is to deduce the effect of an action, and in order to do that one tries to eliminate potential noise factors.

A potential weakness of the experimental design approach is the assumption that an effect measured on a very controlled subset of the population is going to be the same as the effect on the entire population. Unfortunately,

---

Mathematical Statistician, USDA Forest Service, Forest Inventory and Analysis, Southern Research Station, PO Box 2680, Asheville, NC 28802, USA.

noise is reality, and when one eliminates noise, one may also be eliminating major segments of the population of interest and their corresponding differences in response.

This realization in other industries has given rise to such areas of study as process control, updating, and calibration techniques. In forestry, the term "localizing" is often used in reference to adapting volume and/or growth and yield functions to local data. Variations of this approach have been labeled "adaptive growth modeling" by some.

PSEUDO-CFI

Let's consider a continuum of control and information with respect to growth and yield studies. We would observe the following relationships among conditional covariances between time 1 (*T1*) and time 2 (*T2*) data,

$$Cov\left(T_2, T_1 \middle| PI\right) \; Cov\left(T_2, T_1 \middle| CFI\right) \; Cov\left(T_2, T_1 \middle| EGP\right)$$

where:

PI = periodic inventories
CFI = continuous forest inventories
EGP = experimental growth plots

Similarly, the conditional variances would be ordered,

$$Var\left(T_2 \middle| T_1, PI\right) \; Var\left(T_2 \middle| T_1, CFI\right) \; Var\left(T_2 \middle| T_1, EGP\right).$$

Naturally, the advantage of the higher variance methods is that the costs are ordered:

$$Cost(PI) \; Cost(CFI) \; Cost(EGP)$$

Realistically, the major driver of the level of effort in industrial forest inventories is cost. What are needed are lowest variance estimates obtainable for a given budget. Because some efforts to increase the covariance between time 1 and time 2 attributes will be inexpensive relative to the amount of increase, while others will not, it is worthwhile to seek an optimal point along the covariance/cost function. Note that it is unlikely that this optimal point falls at either extreme. Therefore, industrial inventories should benefit from the judicious inclusion of CFI features. It is not widely acknowledged that this is possible because the above scales are continuous, and the periodic inventories would not have to conform exactly to strict CFI specifications. Hence, we arrive at PSEUDO-CFI, defined as the family of sample designs that lie between periodic inventories and continuous forest inventory, obtained by formally relaxing the requirements of CFI, hopefully in a manner that nets the greatest decrease in cost for the least increase in variance.

Although the term "continuous forest inventory" or "CFI" has been applied to many different designs, most have a common set of elements:

1. Permanent sample points are used,
2. Regularly scheduled remeasurements are made,
3. Individual trees are stem-mapped, and
4. A reconciliation of sample trees with those existing at the previous measurement is made.

All these elements could be relaxed in different ways, although some would contribute to such an increase in variance that "borrowing" from CFI would be of little worth.

There are many ways in which the first requirement, of using permanent sample points, might be relaxed. This allows a range of choices with respect to cost per unit variance reduction. (Of course, the result of eliminating it completely would be a periodic inventory). It is expected that most useful designs will be somehow related to a permanent list of points. For instance, we could have a permanent list of sample points but not require exact field relocation of all (or any) of the points. Because the cost of approximate relocation of point center is low, while the cost for exact (or very small tolerance) point center location can be relatively high, it could be advantageous to formulate a sample design and the corresponding estimation system for particular levels of relaxation of the relocation requirement. One idea would be to limit the search time for point center once the general location has been reached. When the limit is exceeded, the data could be taken at the "best guess" point location. Alternatively a requirement might be set that each point must be located within +/- a maximum distance, such as that achievable through a geographic positioning system. A workable plan would be to require that x percent of the points be relocated to within a very small tolerance, while the remaining (100-x) percent of the points be relocated to within a larger tolerance.

As with the point relocation requirement, there are many ways in which the regular timing requirement could be relaxed. Feast or famine cycles could be allowed in timing of measurement periods. This would be attractive to landowners that experience fluctuations in business activity. These types of businesses would benefit from being able to collect most of the data while adequate revenues are being generated. Related ideas include allowing different interval lengths between measurements based on a priority classification, or devising a temporally defined subsampling scheme.

Another aspect of CFI, which could be relaxed to various degrees, is the rigor with which sample trees are identified for future relocation. Often trees are both physically marked and their locations are entered into the database. At each successive visit, an extensive reconciliation of the previous measurement's sample trees is undertaken to allow the fitting of individual tree and spatially dependent models. One way to relax this requirement is to define a minimum diameter, below which the trees are not mapped or tagged. Not individually identifying any sample trees is another option. Or tagging could be chosen over stem-mapping because physically marking the trees can be relatively inexpensive while stem-mapping with all its implications, such as having the previous inventory's individual tree data available to the field crew, is relatively expensive.

Relaxing the reconciliation requirement could take the form of requiring only the reconciliation of a subpopulation of the trees, such as the largest or most valuable trees, or of only a subsample of trees. If only a subpopulation of trees is reconciled, then individual tree models could not be calibrated for the remaining population. Subsampling from the entire population is the more satisfying method of relaxing this requirement. Of course, any number of tree subsampling schemes could be devised for permanent identification.

Without much effort, we could use the relaxation of both tree and point relocation and have, as a result, a system that has CFI/SPR (sampling with partial replacement) design qualities. For instance, we could require exact relocation on a subset of points and approximate relocation on the remaining points at short time intervals, while requiring exact relocation of all points at a longer time interval. The degree to which trees are remeasured could be allowed to depend on the point relocation criterion. We would thereby achieve most of the benefit of a CFI design with respect to variance of the growth estimate without incurring the high cost of exactly relocating each point at each visit.

This plan begs the question: how close would we have to get on the approximately relocated plots? The answer to this question is case specific, because it depends on the proportion of exactly relocated plots, the time intervals between measurements, and the growth rates of the populations of interest. Note that you would even expect a growth estimator formed on the less than perfectly remeasured part of the sample (i.e., those trees not included at both measurements) to have a smaller variance than one formed from two spatially independent samples because neighboring trees often share many of the same characteristics. In addition, through time, if point relocation errors were randomly distributed, you would expect trees that are missed at one remeasurement to have an equal probability of being measured in a subsequent time period as trees that were not missed. However, point relocation errors may not be randomly distributed. Further simulation study is needed in this area.

ANALYSIS

Data from a Pseudo-CFI design might be used in several ways. During the first few measurement periods, the data would be used only to adjust the resulting updated estimates. After the design has been in place for a number of measurement periods, the data could be used to directly calibrate the growth and yield equations.

A long-range analytical plan would be to treat existing growth and yield estimators as a prior distribution, collect data on multidimensionally defined subpopulations, and use it to calibrate the original estimators into final or posterior growth and yield estimators for appropriate segments of the subpopulations. This approach would help to correct the erroneous assumption in traditional growth and yield modeling that forest growth is stationary in the statistical sense with respect to time and space.

Mixed Estimation

Because we have information from a wide time interval and want it to give us as accurate a picture as possible of the current state, we should formally account for the fact that estimates derived from more recent data will have a lower variance than those derived from older data. Theil (1971) provides a solution known as mixed estimation, which was discussed in Van Deusen (1989, 1996). The latter work is followed directly here.

For simplicity, assume that we have a large sample, a survey cycle of T time periods, and that we are interested in sample plots that have not been harvested during the cycle. A simple model for our sample data at time $t=1,...,T$ is:

$$\bar{y}_t = \mu_t + \bar{e}_t$$

where $\bar{e}_t$ is an error term with a mean of 0 and a variance of σ_t^2 / n_t, which we would estimate by the usual sample estimator. Now let $\hat{y}_t$ represent the prediction obtained from the growth model at time t and $\hat{g}_t = \hat{y}_t - \hat{y}_{t-1}$, where $t = 2,..,T$. A simple model for the time series might then be represented as:

$$\hat{g}_t = \mu_t - \mu_{t-1} + v_t$$

where v_t is an error term of zero mean and λ_t^2 / m_t variance.

Collect the $\bar{y}_t$'s into the vector $\overline{\mathbf{Y}} = [\bar{y}_1, ..., \bar{y}_T]'$, the $\hat{g}_2$'s into the vector $\hat{\mathbf{G}} = [\hat{g}_2, ..., \hat{g}_T]'$, the means into the vector $\mathbf{U} = [\mu_1, ..., \mu_T]'$, and the error terms into the vectors $\mathbf{e} = [\bar{e}_1, ..., \bar{e}_T]'$ and $\mathbf{v} = [v_2, ..., v_T]$.

The matrix representation of the sample data model is then $\overline{\mathbf{Y}} = \mathbf{U} + \mathbf{e}$.

With the definition of two design matrices:

$\mathbf{D}_1$, a *TxT* matrix in which the diagonal elements are 1 and the off-diagonals are 0 and

$$\mathbf{D_2} = \begin{bmatrix} -1 & 1 & 0 & \dots & 0 \\ 0 & -1 & 1 & \dots & 0 \\ . & . & . & . & . \\ 0 & 0 & \dots & -1 & 1 \end{bmatrix}, \text{ a } T\text{-}1 \text{ by } T \text{ matrix,}$$

we can represent the time series as $\hat{\mathbf{G}} = \mathbf{D}_2\mathbf{U} + \mathbf{v}$. Furthermore, we can write the equations in the combined form as:

$$\begin{bmatrix} \overline{\mathbf{Y}} \\ \hat{\mathbf{G}} \end{bmatrix} = \begin{bmatrix} \mathbf{D_1} \\ \mathbf{D_2} \end{bmatrix} \mathbf{U} + \begin{bmatrix} \mathbf{e} \\ \mathbf{v} \end{bmatrix}$$

Define:

$$\Sigma_1 = \begin{bmatrix} \sigma_1^2/n_1 & \sigma_{12}/n_{12} & \cdots & \sigma_{1T}/n_{1T} \\ \sigma_{21}/n_{21} & \sigma_2^2/n_2 & \cdots & \vdots \\ \vdots & \cdots & \ddots & \vdots \\ \sigma_{T1}/n_{T1} & \cdots & \cdots & \sigma_T^2/n_T \end{bmatrix}$$

and

$$\Sigma_2 = \begin{bmatrix} \lambda_2^2/m_2 & \lambda_{23}/m_{23} & \cdots & \lambda_{2T}/m_{2T} \\ \lambda_{32}/m_{32} & \lambda_3^2/m_3 & \cdots & \vdots \\ \vdots & \cdots & \ddots & \vdots \\ \lambda_{T2}/m_{T2} & \cdots & \cdots & \lambda_T^2/m_T \end{bmatrix}$$

With independent periodic inventories, the off-diagonal elements in the above two matrices can be assumed to be zero. Although convenient, this assumption would not be valid or desirable in the present context.

The mixed estimator would be:

$$\hat{\mathbf{U}} = \left(\mathbf{D_1}'\sum{}_1^{-1}\mathbf{D_1} + \mathbf{D_2}'\sum{}_2^{-1}\mathbf{D_2}\right)^{-1}$$

$$\left(\mathbf{D_1}'\sum{}_1^{-1}\overline{\mathbf{Y}} + \mathbf{D_2}'\sum{}_2^{-1}\hat{\mathbf{G}}\right)$$

with a covariance matrix:

$$\mathbf{V}\left(\hat{\mathbf{U}}\right) = \left(\mathbf{D_1}'\sum{}_1^{-1}\mathbf{D_1} + \mathbf{D_2}'\sum{}_2^{-1}\mathbf{D_2}\right)^{-1}$$

EXAMPLE APPLICATION – NORTHEASTERN UNITED STATES

The dynamics of forest populations in the northeastern spruce-fir forest are due largely to a spruce-budworm outbreak in the 1980's. Spruce-budworm effects were not a factor considered in the growth and yield functions available for updating the inventory, and the current populations are quite different from any of those upon which the existing models were built. Therefore, a Pseudo-CFI sample design was overlaid on an existing systematic design to continuously monitor and possibly calibrate the dynamic inventory to the changing populations.

The design starts with a permanent randomly placed grid of points (20 by 5 chain spacing) laid over an entire region. The grid points are sampled in an extensive "base" inventory every 15 years, and subsampled every 3 years. We give details of the procedure below.

Sampling Procedure:

1. Photographs of the inventory area will be interpreted to determine the stratum and priority class of each stand every 15 years. The stratum classification will be continuously updated as growth, silvicultural practices, or harvesting actions change a polygon's stratum membership. Each stratum will be classified into one of three spatial sampling intensities, labeled high, medium, and low priority.

2. A permanent base grid of points (5 by 20 chains) will be randomly placed over the region. All points falling outside of the areas of interest are ignored, and the remaining points are numbered from 1 to N. The grid points actually used in the full field sample will be selected every 15 years from these grid points weighted by priority class. Every point in every line will be measured in high priority strata, every even-numbered point in every line will be measured in medium priority strata, and every even-numbered point in every fifth line will be measured in low priority strata. (The starting line will be chosen at random from the first five lines.) Since the grid is permanent, most of these points will be relocated as closely as possible and remeasured at the next full inventory in 15 years; only adjustments due to priority class changes will be made.

3. Every 3 years a systematic subsample of 15 percent of the sample points will be remeasured. During the

initial inventory, the sample points will be numbered from 1 to n beginning at the first sample point of line 1. Then a random number between 1 and 100 will be chosen as the starting point. This and the next 14 contiguous sample points will be included. The next 85 sample points will be skipped. This pattern will be repeated until all sample points in the grid have been worked through. The subsample points will be located with a GPS and monumented. The 15-point cluster was chosen because this is expected to be the number of points on which data can be collected in 1 day (at least in fully stocked stands). All point-level and tree-level measurements will be made. "In" trees greater than 4.5 inches dbh will be measured in a clockwise direction from due north and tagged with an identification number.

CONCLUSION

Pseudo-CFI is a family of sample designs that exploit a particular section of the continuum of potential degree of control in investigations of forest growth and yield. This family of Pseudo-CFI sample designs is not intended to replace controlled experiments for the development of growth and yield equations. It is merely intended as a monitoring mechanism to facilitate the identification of badly behaving populations and provide a reasonable set of data that can be used to calibrate model estimates for these populations. It is arguable that all forest populations are constantly moving away from those upon which their respective growth and yield models were built. What determines the necessity for model calibration is the rate at which the population is moving in relation to the length of time that has elapsed since model development. Because this can not be known in the absence of a monitoring effort, these ideas can and should be applied to all dynamic inventory systems, not just to industrial systems. The reason industrial inventory systems have been stressed here is that these systems, in general, have a much greater investment per acre and have been using dynamic features longer than public sector inventories.

ACKNOWLEDGMENTS

Phil Malerba, Technical Services Manager, Northeast Region, Champion International Corporation, provided many insights that helped to identify the need for Pseudo-CFI. In addition, he provided much of the detail used to convert the theory into an operationally efficient design. The following people reviewed this paper: Dr. William Bragg, Champion International Corporation, Jacksonville, FL, USA, and Dr. Gregory A. Reams, Southern Research Station, USDA Forest Service, Asheville, NC, USA.

LITERATURE CITED

Basu, D. 1980. Rejoinder to comments on randomization analysis of experimental data: The Fisher randomization test, by D. Basu. Journal of the American Statistical Association. 75: 575-595.

Cochran, W.G. 1965. The planning of observational studies of human populations. Journal of the Royal Statistical Society A. 128: 234-265, with discussion.

Cochran, W.G.; Rubin, D.B. 1974. Controlling bias in observational studies: a review. Sankhyä A 35: 417-446.

Green, E.G.; Roesch, F.A., Jr. 1993. Statistical analysis of observational studies with emphasis on forest response studies. In: Rennolls, K.; Gertner, G., eds. The optimal design of forest experiments and forest surveys, Proceedings of a IUFRO S4.11 conference; 1991 September 10-14, London UK: University of Greenwich: 157-166.

Rubin, D.B. 1973a. Matching to remove bias in observational studies. Biometrics. 29: 159-183.

Rubin, D.B. 1973b. The use of matched sampling and regression adjustment to remove bias in observational studies. Biometrics. 29: 185-203.

Rubin, D.B. 1974. Estimating causal effects of treatments in randomized and nonrandomized studies. Journal of Educational Psychology. 66: 688-701.

Rubin, D.B. 1976a. Multivariate matching methods that are equal percent bias reducing, I: some examples. Biometrics. 32: 108:120.

Rubin, D.B. 1976b. Multivariate matching methods that are equal percent bias reducing, II: Maximums on bias reduction for fixed sample sizes. Biometrics. 32: 121-132.

Rubin, D.B. 1978. Bayesian inference for causal effects: The role of randomization. The Annals of Statistics. 6: 34:58.

Rubin, D.B. 1979. Using multivariate matched sampling and regression adjustment to control bias in observational studies. Journal of the American Statistical Association. 74: 318-328.

Rubin, D.B. 1980. Discussion of randomization analysis of experimental data: The Fisher randomization test, by D. Basu. Journal of the American Statistical Association. 75: 591-593.

Rubin, D.B. 1986. Which ifs have causal answers. Comments on statistics and causal inference by P.W. Holland. Journal of the American Statistical Association. 81: 961-962.

Theil, H. 1971. Principles of econometrics. New York: John Wiley & Sons.

Van Deusen, P.C. 1989. Multiple-occasion partial replacement sampling for growth components. Forest Science. 35: 388-400.

Van Deusen, P.C. 1996. Incorporating predictions into an annual forest inventory. Canadian Journal of Forest Research. 26: 1709-1713.

Wickramarante, P.J.; Holford, T.R. 1987. Confounding in epidemiologic studies: the adequacy of the control group as a measure of confounding. Biometrics. 43: 752-765.

Wold, H. 1956. Causal inference from observational data. Journal of the Royal Statistical Society A. 119: 28-60, with discussion.

An Annualized Forest Inventory for Nebraska

Hans T. Schreuder and Tom D.Wardle

Abstract.—This paper addresses opportunities presented to states by an annualized forest inventory system, to be conducted by the Forest Inventory and Analysis program of the USDA Forest Service, and concerns about these inventories. The importance of a balanced approach in assessing timber and nontimber attributes is emphasized, and the paramount importance of maintaining and even increasing the credibility and utility of inventories is discussed. Annualized inventories appear to be a very good idea for Nebraska if implemented properly. A key issue facing forestry and agriculture in Nebraska is used to illustrate how annualized inventories can be more informative than the previously implemented periodic surveys in managing a state's land resources.

Traditionally, the USDA Forest Service's inventory of the nation's forest resources has involved a periodic visit to each state, with the stated intent of a 10-year cycle. When a given state's "turn" came, Forest Inventory and Analysis (FIA) field crews would move to that state and measure plots as quickly as possible; when the field work was complete, data analysis would begin and the crews would move to the next state in the sequence.

An annual inventory system is based on the concept of sampling a certain number of FIA plots annually in each state. This approach was developed in collaboration among the Minnesota Department of Natural Resources, the FIA unit of the North Central Research Station, and the Multiresources Inventory Project of the Rocky Mountain Research Station. The idea was to test the system initially in the Aspen /Birch Survey Unit of northern Minnesota and, after a few years, apply it in other parts of the state. This approach was intended to be cost-neutral relative to the periodic survey, and this was shown to be true (Schreuder *et al.* 1998). The original plan was to divide the permanent plot database for a state into one or more "disturbed" strata plus an undisturbed stratum, using Landsat TM data. What constitutes disturbed depended on what could be consistently assessed as such from the TM data, such as clearcut plots. Then a large sample of disturbed plots and a small subset of undisturbed plots would be remeasured annually, subject to the constraint that all plots would be remeasured over a 20-year period. The thinking was that growth, mortality, and other change on the undisturbed plots could be predicted using models, with only a few sample plots being remeasured to verify the validity of the models. The disturbed plots could not be modeled so information would be gathered by visiting a large sample of these plots on the ground.

Another annualized inventory approach, Southern Annual Forest Inventory System (SAFIS) was introduced and quickly accepted as the way to conduct surveys in the Southern US. In SAFIS, a certain percentage of the plots in the state would be remeasured each year, with the intent of measuring 20 percent of the plots each year across the state without regard to disturbance.

In 1998, the "Agricultural Research, Extension, and Education Reform Act of 1998," Senate Bill 1150, was passed and signed into law. It mandates that 20 percent of all FIA plots in each state be measured each year. The purpose of this paper is to examine the impact and opportunities of this mandate in Nebraska and similar states.

BACKGROUND

Nebraska's commercial forest land base is small, and the industry that depends on it is also small and widely scattered. Nebraska's resource, however, produces all the benefits that other states' resources produce, and its forest industries, while fewer in number, are as important in their local economies as anywhere. Other values, including soil protection, water quality protection and enhancement, wildlife habitat, and recreation are also important. FIA needs to address this wide range of interests even better than in the past for maximum utility to key user groups such as the State Forest Services of Nebraska and other Great Plains states. The limited amount of forest land in Nebraska relative to other states means that only a small number of sample plots are used currently in the FIA survey and selecting only 20 percent of these plots each year constitutes a small sample.

Mathematical Statistician, USFS, Rocky Mountain Research Station, Fort Collins, CO, USA, and Deputy State Forester, Nebraska State Forest Service, Lincoln, NE, USA.

The responsibility of the FIA units is to inventory the forest resources of the nation. Thus, it is important that the annualized inventory apply in all states, not just in the major timber-producing ones. Also, it is critical that analyses cover other forest outputs as well as wood fiber. The shift in the USDA Forest Service in recent years from interest in timber products to interest in all forest products is a necessary and welcome evolution that is continually forcing change in the work done by FIA.

FOREST INVENTORY AND ANALYSIS IN NEBRASKA

In Nebraska, FIA data are used for essentially the same purposes as in other states. There are, however, significant differences. Nebraska's forest industry is characterized by small plants that are widely scattered and not organized into trade associations. Industry requests to FIA and the Nebraska Forest Service for data are infrequent and unpredictable. Most sawmills in the Plains states are very small and, in many cases, the quantity of wood available to a mill is not a serious concern. In most locales, timber does not play a dominant role but is one of many benefits derived from the forests. FIA data are used by the Nebraska Forest Service to understand the resource, to help make predictions on future forest condition, and impacts on range and wildlife resources, and to help understand the influence of change in the agricultural environment on the forest resource itself and vice versa.

Nebraska's most recent forest inventory was conducted in 1994 and involved 431 sample plots. The inventory found that timberland totaled 898,400 acres of which 174,000 acres were ponderosa pine and 110,000 acres were eastern redcedar or eastern redcedar/hardwood. The remainder was made up of hardwoods of various types. In 1994, in total, the state contained 947,700 acres of forest and 1,253,500 acres of nonforest land with trees, scattered throughout more than 49,000,000 acres.

Previous inventories were conducted by FIA in 1955 and 1983. Because of the long delay following the 1955 inventory, the state conducted its own survey in 1977 using FIA procedures, but not their plots. In this situation, it is meaningless to speak of an average cycle (time interval) for inventories. In the past 2 decades, the North Central Station has set a goal of a 10-year cycle but has been unable to maintain it. The long and unpredictable cycle length is perhaps the greatest disadvantage of the current system. In a state such as Nebraska, which is dominated by production agriculture, a forest inventory that comes out perhaps every 10 or 12 years is not very visible. People forget about it and are unaware that useful data are available to assist them in managing the land resource. Agricultural interests get data on some crop and livestock issues several times a year, monthly, or even daily where prices are concerned. Forest inventory data have, as a result, had little impact on agricultural decisions.

An important advantage of the current system is that it involves a periodic visit by a credible and neutral outside entity and the results are accepted. To the extent that states become more involved in the data gathering and analysis, the idea of a largely unbiased inventory could be eroded. A shorter cycle, if it brought with it the perception of less credible data, would not be the choice of the Nebraska Forest Service.

Some states, perhaps because of the great importance of their timber resources, have been successful in going to their state legislatures, or forest industry groups, and requesting funds each time a Forest Service inventory was scheduled. For at least some states, it would likely be easier to obtain a relatively small amount of funding on an annual basis.

OPPORTUNITIES PRESENTED BY AN ANNUALIZED SYSTEM

More frequently updated inventory results may well increase the visibility of forestry information in states that are heavily influenced by agricultural interests such as Nebraska. Annualized updates will mean more awareness and acceptance for forest inventory data, and greater awareness of the forest resource by all interests should result in improved land management programs. In addition, more users and more frequent uses of FIA data should, over time, improve the quality and the importance of the data. A real opportunity exists to develop consistent, comprehensive, well-documented, and user-friendly computer programs for estimating and analyzing the national resources, something that has been conspicuously lacking in FIA.

CONCERNS WITH AN ANNUALIZED INVENTORY SYSTEM

Concerns have been raised about the potential for FIA to direct more of its analytical and data processing resources toward the more heavily forested states. In the old system, there was a clear focus on each state each time its inventory was conducted. The national mandate of FIA would be weakened if the annualized system's requirement for nearly continuous analysis of data gathered in the major timber producing states would be met at the expense of the smaller ones.

An annualized inventory system will produce some results each year. A potential danger is that some of these estimates will be accepted as reliable even when they are not. Annual estimates for states with many sample plots, such as Minnesota, will be reliable, but this may not be true in Nebraska. The reliability of the estimates generated and the closely related impact of an annualized inventory process on confidence intervals need to be addressed.

Other concerns relate to budgeting. What, for example, would be done if, 4 or 5 years into an annualized system, budgets were cut and field work had to be interrupted? Under the traditional system, the cycle length would be extended by whatever time period the budget problem dictated, but the statistical validity of the end result would not be compromised. Similarly, if Nebraska had a perceived serious problem in its western part, so that most or all of the ground sampling should be done there in a given year, how might this affect the estimation and analysis? Would it be feasible to interrupt the annual sample with a one-time inventory focusing on a specific geographic area? Intensification of the sampling grid, if the budget were available, is straightforward, but other approaches focusing primarily on subsets of attributes should be considered.

DISCUSSION

At present an approach that does not include disturbance detection appears to be the logical one to use initially for annualized surveys. The simplicity that results from not having to use such detection before implementing the sample of ground plots makes the approach much easier to implement and more generally applicable. Assuming 20 percent of the plots are measured each year, approximately 86 field plots will require measurement annually in Nebraska. This number of plots is based on the total number of plots from the 1994 inventory and could change if the sample grid or expansion factor or other characteristic of the inventory design changes.

The main product of an annualized inventory is the annual database, which should be made available immediately to the State Forest Service and other interested user groups. FIA in the North Central Station may need to set up a full-time position for a statistical analyst to encourage proper and full use of the data by states and other user groups. The best approach to staffing is likely to combine national level expertise for support and coordination with increased local capacity. Development of consistent, comprehensive, user-friendly estimation and analyses programs should be a high priority for FIA to facilitate such interactions. The FIA Table Generator Web site, operated by the Southern FIA office in Starkville, Mississippi, is an excellent example of the kind of user-friendly access to data that can be established. Such necessary interaction between the Plains states and FIA will have the further benefit of encouraging a better balance between timber information and other forest resource information in future FIA surveys of the states.

We propose that the standard core tables generated by FIA should be published every 5 years for Nebraska using simple averages and totals for the entire 5-year data set, until better weighting methods are available for combining the information from the 5-year period. For some parameters, such as area under forest or change in forested area, statewide Thematic Mapper coverage used in conjunction with even only 86 ground plots could yield reliable annual estimates. For other parameters, improved models should be developed by researchers, using plot-level models, single-tree models, and multiple imputation to update plots not remeasured in the years of interest. Such updating techniques should be developed to accommodate user groups but should not be used to update the plot information in the actual public database until proven to be completely reliable. Modeling might become useful for projecting the current inventory results into the future so the implications of continuing current trends could be evaluated.

With annualized inventories, opportunities might exist to sample specific parts of Nebraska more intensively at some times to investigate something of particular interest. This would be accomplished by either obtaining special funding to intensify the sample in the area of special interest, or by using low altitude photography to gather information, or both. Satellite imagery might also play a role.

The possibility that the 20 percent annual sample might not be sustained has to be considered. Changes due to the increased sampling for issues of special interest or any change that makes it impossible to maintain the 20 percent sample each year will cause differences in probabilities of selection of plots. This complication in analysis should be accommodated immediately in estimation and analyses programs developed for annualized inventories.

Examples of special interest in Nebraska include assessing the impact of single-tree selection cutting, often involving only a few trees per acre, used with black walnut, assessing the impact of the seed-tree partial cuts now being used in ponderosa pine stands, and monitoring the proliferation of eastern redcedar in the state. The following data are from the 1983 and 1994 Nebraska inventories:

Area and number of eastern redcedar in Nebraska

	1983	1994
Area (thousands of acres)	42.2	109.8
Number of trees(thousands)	18,719	30,023

(Source: Table 4, Area of Timberland by County and Stand Size Class, and Table 11, Number of Growing-stock Trees on Timberland by Species and Diameter Class, FIA Table Generator web site maintained by the Southern FIA unit at Starkville, MS, World Wide Web address: http:\\www.ssrsfia.usfs.msstate.edu/scripts/ew.htm).

Although these figures indicate a significant increase in the occurrence of eastern redcedar, many important questions remain unanswered; for example, was the increase consistent from year to year or was it concentrated in specific years? Was there an increase in the first few years after the 1983 inventory but that has now ended? An annualized system would help answer such questions. This change in Nebraska is so significant that even the 86-plot, 20 percent annual sample, resulting in about 7-8 plots in the eastern redcedar resource might at least give a hint that something is going on and could lead to follow-up work. Certainly 2 or 3 years of data would. For a full understanding, it is likely that more data would be needed, e.g., by acquiring and interpreting low altitude photography that should be cheaper than measuring additional ground plots. In this case, the cost of the additional work should probably be met by the Nebraska State Forest Service. If the same phenomenon is observed in adjacent states, there might be a case for increasing the frequency of sampling in each, perhaps funded by the affected states. The traditional FIA system would require that we wait another full cycle of perhaps 10 or more years before investigating the phenomenon further.

Under an annualized system, field crews will probably be located in the "center" of a group of plots assigned to them for measurement. In heavily forested states, crews will be able to work relatively close to home, but that won't be possible in the Plains states. We recommend that two field crews of two people each be stationed in a central location such as Lincoln, Nebraska, or perhaps one crew in Lincoln and another in Rapid City, South Dakota. Other cities may be selected provided the crews are located close to their areas of responsibility. Such crews, for example, might be responsible for Nebraska and parts or all of the surrounding states. These crews, perhaps partially state funded, could also collect harvest and production data from local mills, not a usual responsibility of FIA field crews. In addition, it may be possible for them to collect forest health or other data, again not an activity typically associated with FIA field work.

Whether permanent FIA crews or contract crews should be used for annualized inventories needs to be addressed. Both approaches have clear advantages and disadvantages. In either case, the crews need to be supervised by FIA staff to help maintain the quality and credibility of the data collected.

An annualized system presents a real opportunity for obtaining a better quality database than was possible previously. Because people from the Nebraska State Forest Service and other users will examine the data each year, obvious errors will be detected more quickly and corrected. If FIA can standardize its basic assessment procedures, it should be possible to improve the quality of the data further. National coordination of the annualized inventories is critical for quality assessment and quality control procedures. Quality assessment and quality control crews from other FIA units should be used to ensure consistency and to obtain more unbiased estimates of the measurement errors made on the plots.

Fast, easy electronic access will be much more important under an annualized system than under a periodic system. User access to the data, with proper safeguards, needs to be facilitated right from the start. For example, the capability of "on demand" printing by individual users at their own computers should be available. In such an environment, a user could work at his or her own computer, access the data, generate tables, and print them as needed. This would make FIA data much more available to users and would free FIA from having to predict user needs and produce all of the tables that might be needed. National coordination of this computerized access will be important.

Integrating or merging the remote sensing phases for inventory and monitoring by FIA of the USDA Forest Service and the Natural Resources Inventory (NRI) of its sister agency, the National Resources Conservation Service, is very desirable, but integrating the ground sampling phases is premature at this time. There are political problems currently with integrating the field work, but a joint remote sensing process in which relevant remote sensing information for both agencies is collected and used to locate the field plots to be measured by the appropriate agency should be attainable. Such coordinated monitoring would be useful, for example, in the issue of the increase in eastern redcedar on both agricultural and forest land from 1983 to 1994.

IMPLICATIONS FOR THE FUTURE

Given that field crews work independently, there will be a need for cross-checking in different states and, in fact, across the country. Having the work checked by people who do not normally work closely with the field crews should result in a more unbiased quality assessment. With the current, highly desirable push for national consistency, there are opportunities to do this nationwide.. Perhaps something like an "FIA crew of the year" award might be desirable. An award, for example, might include such a crew doing quality assessment work in one or two locations of their choice, anywhere in the country.

It is also possible that, given a more frequently updated and thus more useful data source, Nebraska and other states that have not been able to contribute significant resources to the FIA process may be able to do so. For example, many states currently acquire satellite imagery for a variety of purposes. Perhaps, in the future, states could contribute imagery for the FIA process, thus helping to maintain an annualized forest inventory system and assuring themselves of having access to the best resource data available. In-kind contributions of office support or similar state assistance might also be considered.

Increased state and other user group involvement could have mixed results. To the extent that such users contributed resources to annualized inventories, the contributions could be favorable if not relied on, but they might be unfavorable if relied on and not forthcoming. The basic responsibility, it would seem, should remain a federal one with state or other user involvement adding sampling intensification or other improvements as deemed desirable by such users.

SUMMARY AND RECOMMENDATIONS

We welcome the shift in FIA policy to annualized inventories. If handled appropriately, it will give such data higher visibility and credibility in states such as Nebraska where all benefits derivable from the forests have equal status. The second author, who was originally deeply skeptical of annualized inventories, now sees real opportunities in it for his state.

However, we have some caveats to the above statements in that:

1. The credibility of the FIA inventories needs to be maintained at all costs. This means that the base program should remain funded and supervised by the federal government. It also means that states with relatively small timber production should not get short shrift relative to big timber-producing states in data collection and analysis.

2. We welcome the change in the USDA Forest Service policy to emphasize better balance between the various benefits derived from the forest resource. This change needs to be expressed more clearly in FIA, and the Nebraska Forest Service is well positioned and willing to help achieve this. We encourage the use of Nebraska as a test site for merging the remote sensing phases of FIA and NRI, anticipating that it will facilitate the production of reliable annual estimates of change in forested areas. Opportunities exist for using high-resolution photography to give improved, relatively cheap estimates of mortality, removals, regeneration, and tree heights in forestry, as well as similar parameters in agriculture and range surveys.

3. "Updating" plots that were not re-measured in the field using models, including multiple imputation procedures, should not be used for compiling public databases until the models are fully tested and proven reliable through the standard scientific process complete with peer review and publication in credible scientific journals. But models should be developed for use by the appropriate user groups (Schreuder and Reich 1998) and for updating purposes.

4. Decisions about the number and location of FIA permanent crews or contract crews, their supervision, and the ensuring of national QA/QC standards should be made in full consultation with the states involved. Perhaps crews could collect harvest and production data as well as the traditional FIA information.

5. The basic product of the forest inventory should be the annual database made available in a form readily usable by State Forestry staff and other user groups. At 5-year intervals, the traditional FIA core tables should be produced by a well-documented, consistent, comprehensive, and user-friendly national computer program. FIA should work closely with State Forestry and other organizations to foster intelligent use of annual, but limited, data sets and to point out opportunities for possible follow-up including the collection of additional state or privately funded data.

LITERATURE CITED

AFIS. 1992. Annual forest inventory system problem analysis. (Unpublished document.) U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis Unit. 51 p.

Schreuder, H.T.; Reich, R.M. 1998. Data estimation and prediction for natural resources public data sets-what is desirable? Res. Pap. RM- . Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. (in press).

Schreuder, H.T.; Gregoire, T.G.; Wood, G.B. 1993. Sampling methods for multiresource inventories. New York, NY: J. Wiley and Sons.

Schreuder, H.T.; Hansen, M.; Kohl, M. 1998. Relative costs and benefits of a continuous and a periodic forest inventory in Minnesota. Environmental Monitoring and Assessment (in press).

Effects of Different Definitions on Forest Area Estimation in National Forest Inventories in Europe

Berthold Traub, Michael Köhl, Risto Päivinen, and Olaf Kügler

Abstract.—International forest statistics such as those provided by the UN/ ECE-FAO Temperate and Boreal Forest Resource Assessment (TBFRA) are typically compiled from national surveys. However, the national systems of nomenclature as well as the definition of the attributes often vary considerably. The European Commission, DG VI, initiated a study to investigate the potential of a European Communication and Information System (EFICS). In the framework of the EFICS study, the effect of different definitions of forest key attributes was investigated. The main focus was on the forest area and growing stock attributes.

The study presented here shows the effect of different forest area definitions, applied to artificially generated forest pattern types, which are typical for southern, central, and northern European forests. In a simulation study, forest area was estimated according to crown coverage, width, and area criteria, applied in the 19 European countries. Forest area differed by up to 13 percent. The effect of different forest area definitions is highly correlated with the amount of area covered by open forest types. Moreover, different rules to delimit the potential forest area from non-forest land have been proven to be very decisive for forest area estimates.

To collect, coordinate, standardize, and distribute data of the forest sector, the European Forest Information and Communication System (EFICS) was launched by an EC regulation in 1989. In 1995, a study on EFICS was started to investigate the potential, feasibility, and realization efforts of EFICS (European Commission 1997). The EFICS study focused on the possibility of harmonizing national information on forest resources. Part of this study was done to investigate the effect of different assessment techniques, definitions, and measurement rules on forest resource information by the integration of national assessments. The study provided quantitative and qualitative figures about the variation of different key statistics caused by this heterogeneity of definitions. On the basis of those results, the need for harmonization efforts with respect to costs and benefits can be judged.

This paper focuses on the effect of differences in national forest area definitions when combined with European forest statistics, which was quantified by means of a simulation study. The assessments of forest area according to the methodology applied in the European Union (EU) Member States as well as in Norway, Switzerland, Liechtenstein, and Iceland (called European countries here), were simulated to facilitate a comparison between the different systems applied.

Most of the results presented in forest inventories are ratio estimates that relate attributes, such as total volume, to unit area, i.e., the forest area of the country. Therefore, the definition of forest area is of major concern, because it affects all area-related results. Individual forest area definitions applied in Europe are presented in table 1. The main criteria included in the definitions are width of forested patch, crown coverage, and size of forested area. Further criteria are productivity and the height of trees. These measures determine whether land covered by trees is assigned to forest or non-forest. The national forest area definitions consist of an individual set of these criteria with different minimum threshold values.

Forest area structure ranges widely in Europe from the Mediterranean types to those occurring in hilly areas and lowlands of central and western Europe to forests in the northern, boreal regions. Changes and differences in the spatial structure are due to differences in climate, soil, due to altitude and geographical location (natural timberlines or coniferous limit in the alpine or northern regions) and also due to recent and historical activities of humans. In an open forest type, changing the minimum crown cover

---

Research Forester, Swiss Federal Institute for Forest, Snow and Landscape Research, Birmensdorf, Switzerland; Professor, Dresden University of Technology, Faculty of Forest- Geo- and Hydro Sciences, Chair of Forest Biometrics and Computer Sciences, Tharandt, Germany; Deputy Director, European Forest Institute, Joensuu, Finland; and Graduate research assistant, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, respectively.

Table 1.—*Forest area definitions in Europe (from Köhl* et al. *1997)*

Country	Minimum width	Minimum crown cover	Minimum area	Minimum production	Region/ comments
	Meters	*Percent*	*Hectare*		
Austria(A)	10	30	0.05	-	central
Belgium(B1/2)	9 /25	-/20	0.01/ 0.05	-	central[1]
Denmark(DK))	20	30	0.5		north[2]
Finland(FI)	-	-	0.25	1m^3/ha/a	north
France(F)	15	10	0.05		central[3]
Germany(D)	10	-	0.1	-	central
Greece(GR)	30	10	0.5	-	south
Iceland(IC)	-	-	0.25		north
Ireland(IR)	40	20	0.5	4 m^3/ha/a	central
Italy(I)	20	20	0.2	-	south
Liechtenstein(LI)	25 to 50	20	-	-	central[4]
Luxembourg(LU)	-	-	-	-	central
the Netherlands(NL)	30	20	0.5	-	central
Norway(N)	-	-	0.1	1 m^3/ha/a	north
Portugal(P)	15	10	0.2	-	south
Spain(SP)	20	5	0.2	-	south
Sweden(S)	-	-	0.25	1 m^3/ha/a	north
Switzerland	25 to 50	20	-	-	central[5]
the United Kingdom(UK)	50	20	2		central

[1] Walloon region / Flemish region.

[2] Trees in the forest should be able to grow taller than 6 m.

[3] 500 stems/ha with dbh < 24.5 cm.

[4] Same definition as CH.

[5] Functional relationship between minimum width and minimum crown cover.

threshold in the definition can greatly affect the total amount of estimated forest land. As minimum crown cover threshold values decrease, forest areas should steadily increase. In areas where forests mainly consist of small patches, alleys, or gallery forest with closed crown canopy, the criteria width and forest area are more decisive and the crown cover criterion should then play a minor role.

Kleinn (1991) investigated the effect of varying minimum crown cover values on forest area estimation. He showed the relationship of different minimum values; the spatial structure of the forests; and the size of the reference area; and found a high sensitivity of the crown cover criterion in open forest types. According to Kleinn, the effect of the size of the reference area has proven to be "not as obvious and easy to describe" as the effect of the crown cover criterion.

In this study, the effect of different minimum threshold values of the criteria crown cover, width, and size of forest area will be quantified by simulation. The results of the simulation study indicate the variation of forest area statistics resulting from revisions of the forest area definition, as they were suggested, for example, for the Temperate and Boreal Forest Area Assessment 2000 (TBFRA 2000) (Nyyssönen and Ahti 1996). It can be expected that figures of forest area change will be substantially affected by those revisions, resulting in a lack of comparability in time.

METHOD

Forest/non-forest images were generated by computer for the simulation study. The images consist of a binary set of 800 x 800 pixels, which represent a distribution of single trees (fig. 1). Four main types of forest spatial patterns were investigated. Image 1 shows a sparsely distributed forest type with a high number of single trees and a gradual transition between forest and non-forest land. Image 2 represents a clustered type of forest where a clear border exists between forest and non-forest land. Images 3 and 4 in figure 1 are composed from different proportions of images 1 and 2 to simulate transitions between these basic patterns.

Forest Cover Assessment Procedure

In national forest inventories, forest size is often assessed by using a systematic sampling of aerial photo plots,

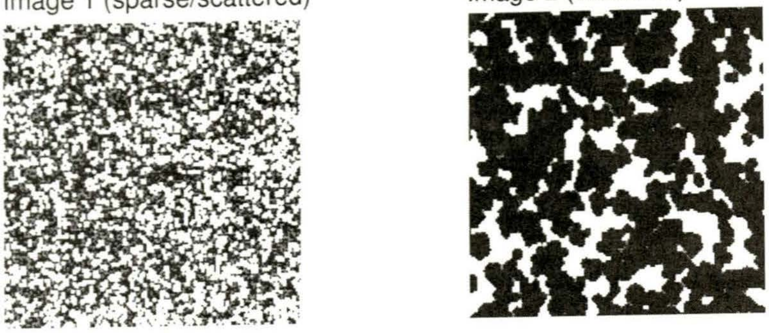


Image 1 (sparse/scattered)

Image 2 (clustered)

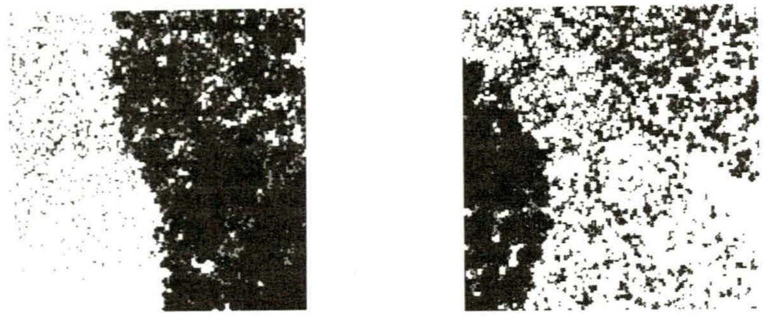


Image 3 (sparse/clustered)

Image 2 (clustered/sparse)

Figure 1.—*Artificially generated forest cover structure types after delineation process (distance 35 m). Black: area covered by tree crowns (each pixel represents the vertical projection of a tree crown); gray: potential forest area (forest land), not covered by tree crowns; white: non-forest land. Each image consists of 800 x 800 pixels with a resolution of 10 x 10 m (images kindly provided by Kleinn* et al. *1995).*

distributed in a grid over the entire area of interest. This procedure is applied in several European countries, but the techniques used are quite different. In this study, the method of the second Swiss National Forest Inventory (NFI) for forest/non-forest decisions on photo samples has been applied (Köhl 1997, Keller 1999). Each plot is interpreted to decide whether the area covered by the plot belongs to the forest or not. The photo plot sampling was simulated on the computer-generated images and can be divided into three steps:

Step 1: Delineation phase

To assess quantitative values of attributes used in forest area definitions, i.e. crown cover, size, and width of forest area, the potential forest area, subsequently called *forest land,* has to be delimited. The measurements of the three criteria have to be applied within these boundaries. According to Kleinn (1992), "an exact boundary has to be found when line transects are used as sampling techniques." This problem can be transferred to the measurement of the width of forest patches. If trees are distributed sparsely with pronounced gaps between closed forest patches, a decision has to be made about which trees belong to *forest land* and which are single trees located in non-forest land. For this reason, Zingg and Bachofen (1988) established a delineation rule based on a threshold value for the maximum distance of single trees from a forest patch to define a *forest land* boundary. This procedure can be interpreted as a pre-step of the forest area estimation. In the simulation study, delineation distances of 25, 35, and 50 m were applied in order to investigate the importance and impact of the delineation rule. The delineation step modifies the original images, which consist of single trees, to new images subdivided into two land categories: *forest land* (potential forest area) and *non-forest land.* The proportion of each category depends on the delineation distance.

Step 2: Simulation of photo plot samples

After the delineation procedure, the forest cover percentage was calculated by systematic sampling. For each sample located within or near *forest land*, a forest/non-forest decision was made according to the definitions of the European countries. About 6,000 squared samples of 50 x 50 m systematically distributed in a 100 m grid were drawn from the images.

The forest cover percentage of the entire area was calculated from the simulated photo plot sampling procedure. It is defined as the quotient of plots assigned to forest and the total number of sample plots drawn from the image times 100. If the plot center is located in *forest land*, the forest/non-forest decision is made according to the minimum threshold values for crown cover, size and width of the forest area. If the plot center is located in *non-forest land*, close to the forest borderline, the length of the shortest virtual line intersecting the plot center and two borderlines are measured instead of the width of the forest area patch. If the length of this line exceeds 25 m, the plot is assigned to non-forest.

Table 1 demonstrates the considerable variation in the definitions of forest applied in the national forest inventories of the European countries. The criteria are not used by all countries nor do the threshold values for the certain criteria coincide. Threshold values for minimum crown cover range between 10 and 30 percent, the minimum width values range between 9 m and 50 m, and the minimum area values range between 0.05 ha and 2 ha. Since it was not possible to integrate the criterion "minimum production" in this type of simulation study, the simulation for the northern countries was difficult. Because those countries also do not use forest cover and minimum width as a criteria, the parameters were set to zero. This approach, however, does not completely reflect the forest area estimation procedure of these countries. Päivinen (personal communication 1998) stated that a minimum threshold for crown cover of 20 percent obviously would be a proper value. However, this problem was left unsolved in this study and could be the subject of further studies.

Step 3: Relating the four forest structure types to European regions

The objective of the simulation study was to investigate the effect of the individual country definitions on forest area estimation. The four artificially generated images represent typical pattern types, but they are not evenly distributed over all of Europe. Since the importance of the individual definitions is assumed to depend on the structure types, the results should be weighted according to the proportion to which these types occur in the several regions. The proportions used in this study for northern, central, and southern Europe were derived from questionnaires submitted to the experts of these regions and can be seen in table 2.

In the northern countries, closed coniferous forests cover wide areas. This structure type is represented by image 2. However, in peatlands or in forests near the coniferous timberline, the crown closure decreases, and the forest structures represented by images 1, 3, and 4 occur and are estimated to make up about 40 percent of the forests. In the central and western parts of Europe, forest land is mainly covered by closed forest types. Their typical properties are sharp, well-defined boundaries to the *non-forest land* categories. However, the forest area is lower and the spatial structure of the forests is more patchy than in northern countries. More than 50 percent of the area in central Europe is covered by agricultural land. This and the closed forest cover of central Europe is represented in image 2. Near the forest timberline, open forest types are dominant with gradual transitions from *forest land* to *non-forest land*, represented in images 1, 3, and 4. However, the amount of open forest types is significantly less than in northern countries. In southern locations, gradual transitions from forest to shrub or other wooded land are very frequent, which makes a clear definition of forest and other wooded land difficult. The phenotypes of forest trees occur both as trees and as shrubs. The wide variety of forest structure types leads to a more or less even representation of the four images.

RESULTS

Comparison of the Forest Area Definitions Based on the Basic Structure Types (Images 1-4)

For each image, the forest cover percent was estimated based on the systematic photo plot sampling simulation procedure. The first part of the results refers to the principal structure types of forest pattern represented in images 1-4; the second part refers to the results found for the European regions.

As a primary result, three groups of countries referring to the level of estimated forest cover percentages can be detected (table 3). This result is more or less independent of the forest structure type. Due to the different forest area definitions from each country, the forest cover estimated by the Austrian definition, for example, is always higher than the estimation derived from the Irish forest definition. Luxembourg was excluded from the study because forest area is assessed from maps in this country, where the distinction between forest and non-forest is "normally obvious" (Kalmes 1997). These principal results have also been proven to be independent from the delineation distance. In table 4, the ranges of forest cover estimation derived from the simulation study, referring to a delineation distance of 35 m, are given. The highest value of forest cover estimation range was found for image type 1 (sparse/scattered). The difference of 29.17 percent was derived from the forest cover estimation according to the Norwegian definition and the

Table 2.—*Percentages of the four forest structure types related to the European regions, from a questionnaire submitted to country experts involved in the EFICS study.*

European regions	Image 1 'scattered'	Image 2 'clustered'	Image 3 'mixed 1'	Image 4 'mixed 2'
Northern	10	60	20	10
Central	5	80	5	10
Southern	30	20	20	30

Table 3.—*Levels of forest cover estimation derived from the four image types (fig. 1). The grouping means that the definition of Austria would always lead to a higher forest cover estimation than, for example, the definition of the United Kingdom, irrespective of the structure of the forest to be assessed.*

Level of forest cover estimation	Countries	
High	A, B1, D,	(FIN, IC, N, S)
Medium	B2, CH, DK, F, FL, I, P, SP	
Low	GB, GR, IRL, NL	

Table 4.—*Differences between highest and lowest forest cover percentage estimation (range) of the four forest cover structure types (images 1-4), derived from the photo plot sampling simulation. The results are given for all the countries as well as for a subset of countries from which Finland, Norway, Sweden, and Iceland were excluded. The range of values for all countries were found from the comparison of the definitions of Norway and the United Kindom; those for the subset of countries originate from the comparison of Belgium/Walloon and the United Kingdom.*

Image	1	2	3	4
Range (all countries)	29.17	1.48	8.29	11.75
Range (subset of c)	24.92	1.23	7.42	10.83

definition of the United Kingdom. However, the range for image 1 probably is not accurate since the forest area definitions of Finland, Norway, Sweden, and Iceland do not apply a minimum crown cover or a minimum width as already stated. Since the simulation of the forest area estimation for these countries is based on incomplete definitions, the results have to be interpreted carefully. In the second row of table 4, which is built from a subset of countries excluding Finland, Norway, Sweden, and Iceland, the largest range for image 1 is approximately 25 percent. This result is derived from the definition of Belgium/Walloon and the United Kingdom. The smallest range between forest cover estimations was found in image type 2 (clustered). The difference of forest cover estimation according to the definition of Belgium/Walloon and the United Kingdom is 1.23 percent.

Comparison Between European Regions

To get an idea of the effect of forest area definitions in northern, central, and southern European regions, the differences of the forest cover percentage estimations originating from images 1-4 were related to the shares of forest structure types in the three regions. The values of table 4 are calculated as the weighted mean of the ranges of table 3. The weights refer to the proportions in table 2; the results, which were calculated for a delineation distance of 35 m, are given in table 5. In table 2, it can be seen that the central region is mainly covered by image type 2 (clustered), which means that the range values are strongly influenced by this structure type. The opposite situation occurs with the figures of the southern region where the results were influenced by all images with more or less equal proportions. The largest ranges occur in the southern region because of the high proportion of scattered forest types. The mean range was built mainly from images 1, 3, and 4. Smallest ranges occur in the central region where clustered types are dominant and the mean range is mainly influenced by image 2.

The impact of different delineation distances is shown in table 6. Highest range values between forest cover

Table 5.—*Mean values of the ranges of forest cover estimation (table 4) weighted with the shares of structure types 1-4 related to the European regions (table 2). The results are given for the ranges derived from all country definitions as well as for a subset of countries in which Finland, Norway, Sweden, and Iceland were excluded.*

Region	North	Central	South
Range (all countries)	6.65	4.24	14.26
Range (subset of c.)	5.78	3.68	12.45

Table 6.—*Range values of forest cover estimation derived from the subset of country definitions (excluding Finland, Norway, Sweden, and Iceland) for the European regions as a function of the delineation distance. The bold values correspond to the values given in table 5.*

Region	Delineation distance		
	25 m	*35 m*	*50 m*
Central	4.48	**3.68**	3.02
North	7.19	**5.78**	5.09
South	16.17	**12.45**	10.86

principally occur in the southern regions; lowest range values occur in central regions. It also can be seen that the magnitude of the range values is negatively correlated with the delineation distance, i.e., the effect of definition differences diminishes with increasing delineation distance. If *forest land* area enlarges, the forest criteria, particularly the criteria "width" and "area," obviously lose their sensitivity. This phenomenon leads to an indifference of the certain minimum threshold values for these criteria and thus to smaller ranges of forest cover percentage. As a general result, it can be stated that the effect of varying delineation distances is greatest in regions covered by open forest types. The number of gaps converting from *non-forest land* to *forest land* by increasing the delineation distance in this region is much higher than in areas covered by clustered forest types.

As already stated, the sensitivity of the forest definition criteria is correlated to the structure types and to the delineation rule applied. A differentiated examination of the non-forest assignments should give a clear understanding of the importance of the single criterion. Knowledge about the effect of a specific criterion could support considerations on harmonization efforts in more detail. A non-forest assignment can be caused by one single criterion or by a combination of criteria, i.e., more than one criterion would lead to the non-forest decision. Figure 2 shows that the width criterion most frequently led to the non-forest decision. In this study, this holds true for all regions and steps of delineation distance. The forest area criterion and the combination of criteria play a minor role; their importance decreases with increasing delineation distance. The crown cover criterion is important when the delineation distance is bigger than 35 m. This is an obvious effect of the increasing *forest land* area, which reduces the amount of small and narrow patches and thus diminishes the effect of the criteria "width" and "size" of forest area. If *forest land* increases, the crown cover percentage decreases because the number of single tree crowns is stable. This effect raises the sensitivity of the crown cover criterion. The differences between the three regions are important only for delineation distances bigger

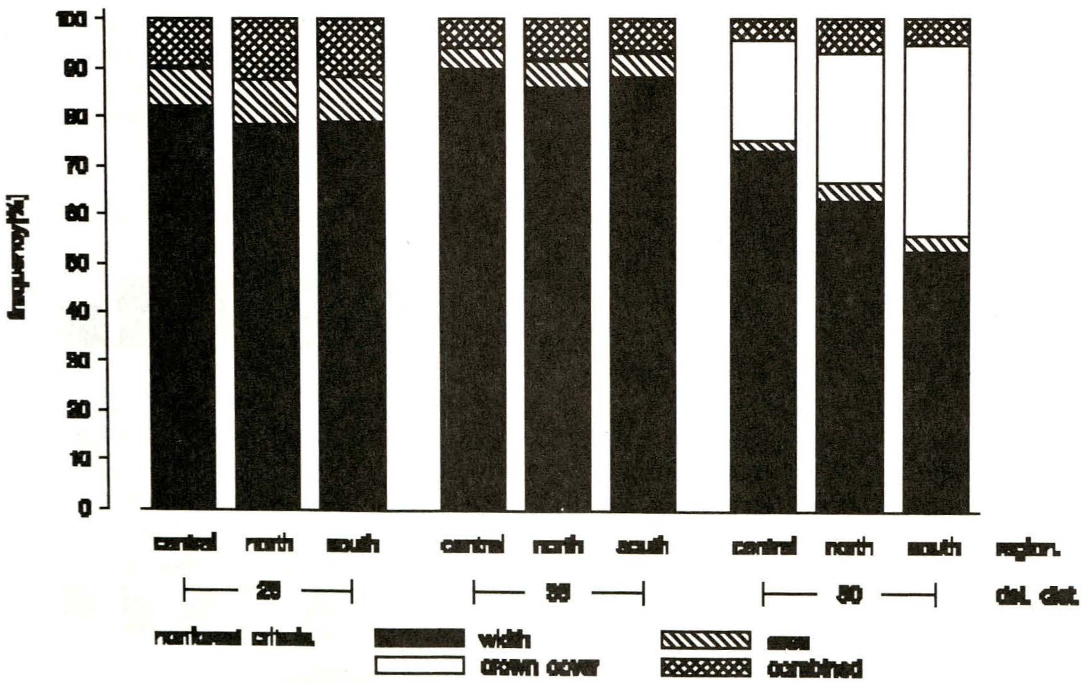


Figure 2.—*Frequency of criteria that led to the decision non-forest, derived from the simulated 50- x 50-m air photo samples located inside or close to the forest land. The results are presented for different delineation distances and separated by the European regions.*

than 35 m. In nearly all cases, the width criterion has been proven to be the most restrictive criterion, which leads most frequently to the non-forest decision.

To get an idea about the effect of certain forest area definitions applied to individual countries, figure 3 shows the effect of country definitions on forest area estimates in Switzerland and the United Kingdom. Positive differences mean that forest area definitions that are applied to a certain country would lead to a higher forest cover compared to the estimate by its own definition. The forest area definition under concern could be interpreted to be more tolerant compared to the definition of the reference country. However, if the definition is more restrictive compared to the reference country, negative differences could occur.

As can be seen in figure 3, the Swiss definition is a moderate one, because some country definitions lead to lower forest area, while others lead to higher forest area in

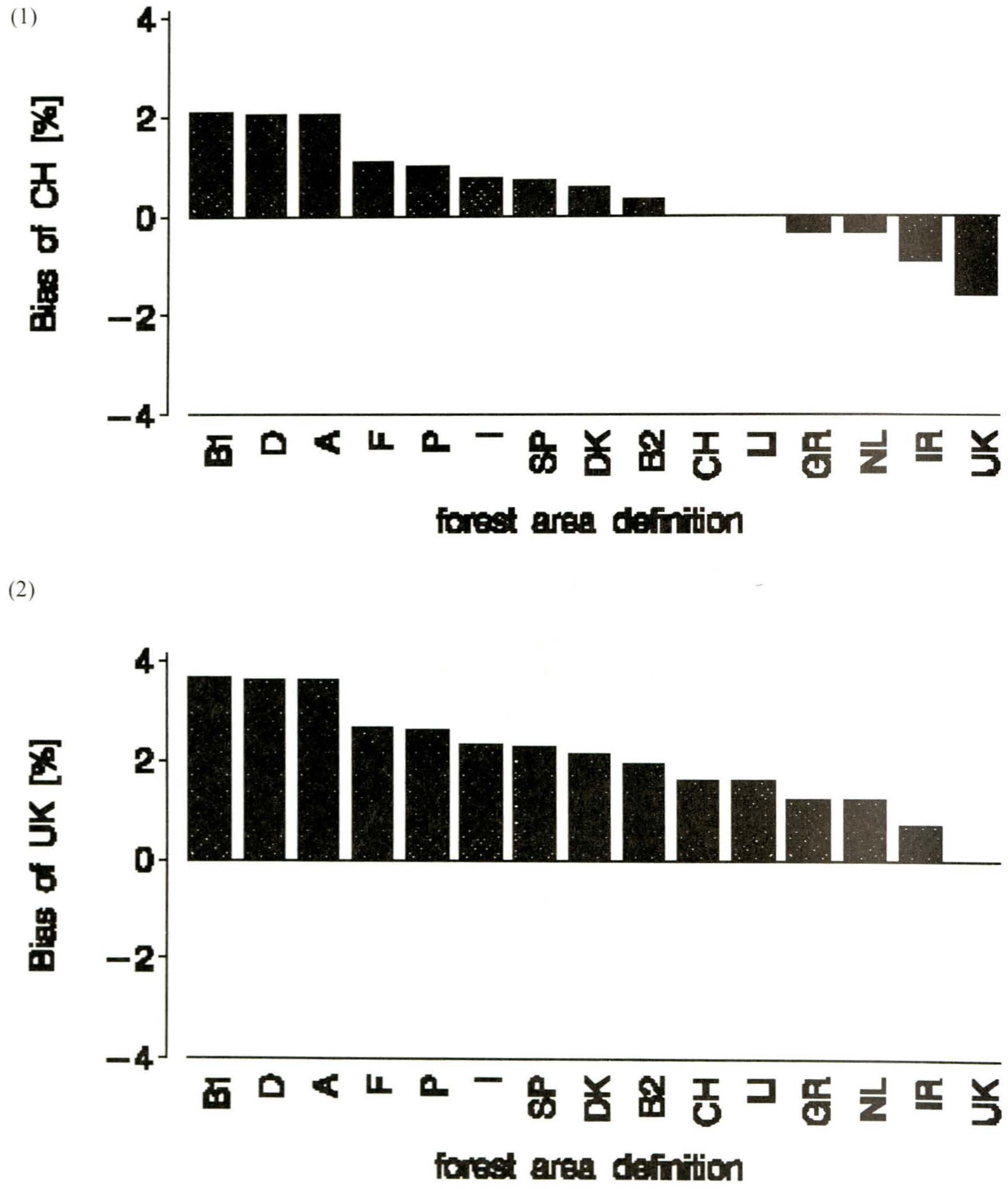


Figure 3.—*Changes of forest cover (bias [%]) for the reference definitions of Switzerland (1) and the United Kingdom(2) as a result of the application of forest definitions of the European countries. A positive bias in the top chart means that the specific country definition would increase forest area compared to the Swiss definition. A positive bias in the bottom chart is the respective to the United Kingdom definition.*

comparison to the Swiss definition. Most tolerant is the definition of Belgium/Walloon, which would increase the Swiss forest by about 2 percent. Most restrictive is the definition of the United Kingdom, which would lead to about –1.5 percent less forest area. This is probably due to the area restriction of 2 ha, which is a far higher minimum threshold value than in other countries. All forest area definitions applied to the United Kingdom forests would lead to an increase of forest area.

CONCLUSIONS

The largest range between forest cover estimations, found from the comparison of the Belgium/Walloon and the United Kingdom definitions, is 24.92 percent and refers to image type 1 (sparse/scattered). The smallest range is 1.23 percent, which is found in clustered image type 2. When combining the theoretical image types to forest patterns according to the proportion they occur in the northern, central, and southern regions, the maximum differences due to the different forest definitions are 5.8 percent, 3.7 percent, and 12.4 percent, respectively. This means that the biggest differences occur for forest types structured similar to image 1. This type mainly occurs in southern regions with a high proportion of scattered forest types and in regions with natural timberlines, as in mountainous (alpine) or northern regions. Lowest ranges occur in the central region where clustered types are dominant.

This leads to the conclusion that harmonization needs are particularly important when forest area statistics are to be compiled from countries located in southern European regions, and from countries with a huge amount of forest approaching the natural timberline in alpine and northern regions.

The importance of the three criteria defining the forest/non-forest decision (width, crown cover, and size of area) depends on the forest structure type. The width criterion has proven to be the most important one for all forests; the crown cover criterion plays an important role in open forest types; and the forest area size criterion plays a subordinate role. It is also important to learn from this study that both the forest area definition and the delineation rule, which separates potential forest land from *non-forest land*, influence the effect of the different definitions. It can be stated that big or "tolerant" delineation definitions lead to small differences of forest cover estimation. Specifically, increasing the delineation distance results in a decrease of the ranges of the forest cover estimates. As can be seen in table 6, these general rules do not depend upon forest structure. Nevertheless, the magnitude of the differences is highest in southern European countries. This leads to the conclusion that the delineation procedure of potential forest area should be treated with great attention in harmonization efforts of the forest area definition.

In this study, forest area definitions from the European countries were applied to artificially generated forest structure types by means of a photo plot sampling simulation. The results from this study should be interpreted as an approach that provides an idea of the dimension of the differences in forest area estimation due to the application of individual country definitions to a certain forest structure type. Some definitions could not be simulated satisfactorily, e.g., those that include minimum height criteria or minimum productivity measures. The implementation of these criteria, as well as the improvement of the comparability of definitions that do not use a unique set of criteria, could be subject to further studies.

ACKNOWLEDGMENTS

This study was partially financed by the European Commission, DG VI, EFICS project. We wish to thank Robert Flies and Louis du Breil de Pontbriand for the permission to publish results of the EFICS study.

We also wish to thank Dr. Peter Brassel, head of the Swiss NFI, for his support and engagement that made it possible to carry out this study at WSL in Birmensdorf.

The following people reviewed this manuscript: Dr. Christoph Kleinn, CATIE, Programa de Investigacion, Turrialba 7170, Costa Rica, and Dr. Marco Marchetti, Adjunct Professor of Forest Inventory, University of Palermo, Italy.

LITERATURE CITED

European Commission. 1997. Study on European forestry information and communication system - reports on forestry inventory and survey systems, Vol. 2. Luxembourg: Office for Official Publications of the European Communities. 660 p.

Kalmes, P. 1997. Country report for Luxembourg. In: Study on European forestry information and communication system - reports on forestry inventory and survey systems, Vol. 2. Luxembourg: Office for Official Publications of the European Communities: 675-710.

Keller, M. 1999. Luftbild. In: Zweites Schweizerisches Landesforstinventar, Methoden und Modelle der Zweitaufnahme. Birmensdorf: Swiss Federal Institute for Forest, Snow and Landscape Research (WSL/FNP). In prep.

Kleinn, Ch. 1991. Zum Waldbegriff in Forstlichen Großrauminventuren. AFJZ, 162. Jg., S. 201-210.

Kleinn, Ch. 1992. On the compatibility of forest inventory results - the problem of compatible forest definitions. In: Wood, G.B.; Turner, B.J., ed. Proceedings of the International IUFRO conference integrating forest information over space and time; 1992 January 13-17; Australia, Canberra: Anutech Pty Ltd: 278-285.

Kleinn, Ch; Traub, B.; Dees, M. 1995. Calibrating forest cover estimates from coarse resolution images with samples of high resolution images - a model study on possible effects of misregistration. In: Köhl, M., Gertner, G.Z., ed. Proceedings of the Meeting of IUFRO S4.11-00 held at International IUFRO world congress; 1995 August 6-12; Tampere, Finland: Swiss Federal Institute for Forest, Snow and Landscape Research (WSL/FNP); Birmensdorf, Switzerland: 210-219.

Köhl, M. 1997. Country report for Switzerland. In: Study on European forestry information and communication system – reports on forestry inventory and survey systems, Vol. 2. Luxembourg: Office for Official Publications of the European Communities: 1019-1093.

Köhl, M.; Päivinen, R; Traub, B.; Miina, S. 1997. In: Study on European forestry information and communication system – reports on forestry inventory and survey systems, Vol. 2. Luxembourg: Office for Official Publications of the European Communities: 1267-1322.

Nyyssönen, A.; Ahti, A., eds. 1996. Proceedings of the FAO expert consultation on global forest resources assessment 2000 in cooperation with ECE and UNEP (Kotka III). Res. Pap. 620. Helsinki, Finland: Finnish Forest Research Institute.

Zingg, A.; Bachofen, H, 1988. Schweizerisches Landesforstinventar, Anleitung fuer die Erstaufnahme 1982-1986. Rep. 304. Birmensdorf, Switzerland: Swiss federal Institute for Forest, Snow and Landscape Research (WSL/FNP). 134 p.

Required Sample Size for Monitoring Stand Dynamics in Strict Forest Reserves: A Case Study

Diego Van Den Meersschaut, Bart De Cuyper, Kris Vandekerkhove, and Noël Lust

Abstract.—Stand dynamics in European strict forest reserves are commonly monitored using inventory densities of 5 to 15 percent of the total surface. The assumption that these densities guarantee a representative image of certain parameters is critically analyzed in a case study for the parameters basal area and stem number. The required sample sizes for different accuracy and probability levels are calculated. The commonly applied inventory densities prove to be insufficient for both parameters considering a generally desired accuracy level of 5 percent (p = 0.05). Results indicate the need for a new reflection on the aspect of representativeness in the framework of forest reserve monitoring.

The most commonly applied method for long-term monitoring of the natural development of woody vegetation in strict forest reserves in Europe consists of a systematic grid of permanent circular plots in combination with a permanent core area (Albrecht 1990, Althoff *et al.* 1993, Broekmeyer and Szabo 1993, Bücking *et al.* 1986). The grid of circular plots provides information on the level of a forest reserve and on the different forest communities or types it consists of, each covering at least its minimum structure area (Koop 1989). The core area gives more detailed information on dynamic processes and covers at least some regeneration units within a forest community. This study focuses on the level of a forest reserve using a grid of circular plots for monitoring purposes. According to Albrecht (1990), such a grid needs to fulfill two aims: first, it should give a representative image of the forest reserve as a whole, and secondly, it should at the same time serve as a network of permanent monitoring plots. Thus, a single circular plot can be treated both as a sample unit and as an area for long-term monitoring of forest dynamics. To achieve both aims, the system of circular plots usually covers from 5 to 15 percent of the total surface of the forest reserve (Albrecht 1990, Althoff *et al.* 1993, Kätzler 1984, Stuurman and Clement 1993). The plots are re-inventoried in 10-year intervals (Albrecht 1990, Stuurman and Clement 1993).

In this study, only the first aim is dealt with for the forest reserve of Liedekerke in Belgium. The objective is to determine the sample size needed to obtain a representative image of this particular forest, in order to evaluate the commonly used inventory density in strict European forest reserves. Therefore, two widely applied parameters (stem number and basal area), globally characterizing forest ecosystems and their natural dynamics, are considered. Sample sizes are determined and compared assuming different accuracy and probability levels for both parameters. To examine their temporal evolution, the results on sample size are compared with those found 10 years later.

MATERIALS AND METHODS

Study Site

The forest reserve of Liedekerke is located in the central part of Belgium and covers an area of 22.5 ha. The elevation ranges between 24 and 36 m above sea level. Its western and northern boundaries are formed by the state forest of Liedekerke (54 ha); the east and the south sides are bordered by pasture and farmland.

A moderately wet, loamy soil occurs throughout the forest, together with some very wet sites in the small valleys. The mesorelief is rather uniform, except for some local depressions.

The forest ecosystem belongs to the Querco-Betuletum type (Quercion) (Noirfalise 1984). Dominating tree species are birch (*Betula pendula* and *B. pubescens*) (approx. 55 percent) and indigenous oak (*Quercus robur* with some *Q. petraea*) (approx. 15 percent).

The forest reserve is a remnant of the ancient "coal forest" or "Carbonaria Sylva." Up to the middle of the 20th century, it was subjected to regular coppicing while heathland still covered more than 40 percent of the surface. The most recent human intervention, which dates back to World War II, consisted of widespread felling by the local population for firewood. For more than 50 years now, this ecosystem has remained unmanaged, which makes it unique for Belgium. During its evolution since

---

Scientific attachés, Institute for Forestry and Game Management, Gaverstraat 4, B-9500 Geraardsbergen, Belgium, and Professor of Forestry, Laboratory of Forestry, University of Ghent, Geraardsbergsesteenweg 267, B-9090 Gontrode, Belgium, respectively.

the 1940's, it showed a steady regression of the heath, culminating in its disappearance in 1970, and a progression of coppice elements into the upperstory (De Cuyper 1993).

Determination of Sample Size

In 1986, a 40- x 50-m grid was installed on a part (12.9 ha) of the forest reserve having a rather homogeneous and uniform forest structure and composition. To investigate sample size for future monitoring of the woody vegetation, 31 circular plots were randomly selected with the intersections of the grid forming their centers (fig. 1). Their size was fixed at 700 m^2 (radius 15 m). Pardé (1961) advises sample sizes between 400 and 800 m^2 for similar homogeneous forest types of comparable age. Such large sample plots were chosen for two reasons. The first reason was to minimize the variance of the estimated parameters caused by the dimension of the sample plot (Rondeux 1993). The second reason was related to their permanent monitoring objective. Because stem number changes in time, larger sample plots have a higher probability of fulfilling the requirement to include a minimum number of trees per plot. Kramer and Akça (1982), Richter and Grossmann (1959), and Spurr (1952) point out that an individual plot should contain at least 25 to 30, 12 to 14, and 20 to 30 trees per plot, respectively. With approximately 70 to 130 trees per circular plot, this particular forest reserve, which is still in its pioneer stage, amply met this requirement.

The first inventory of these 31 plots, covering 17 percent of the total surface, was made in 1986. Every tree with a dbh exceeding 2 cm and taking root in the plot was taken into account. The trees were identified and their diameters were measured with an accuracy of 1 mm. Usually only trees with a dbh ≥ 5 cm are included in the calculation of the mean basal area (Albrecht 1990, Hocke 1996, Kätzler 1984, Stuurman and Clement 1993). To investigate the impact of smaller dbh ranges on the sample size, special attention is given to trees with a dbh ≥ 2 cm. In 1996, the same measurements were repeated.

To determine the sample size (n) for a certain accuracy level (E%) of the parameters mean stem number and mean basal area of all trees, the following formula for simple random sampling can be used, provided the data set approaches a normal distribution (Rondeux 1993, Schreuder *et al.* 1993):

$$n = \frac{t\Delta(s\%)\Delta}{(E\%)\Delta + \frac{t\Delta(s\%)\Delta}{N}} \qquad (1)$$

where s% is the coefficient of variation (= standard deviation divided by the mean of one of the parameters previously mentioned), N the total number of plots needed to cover the whole surface (= population), and t the t-value that can be extracted from the table of a t-distribution for a certain p-value or probability level and

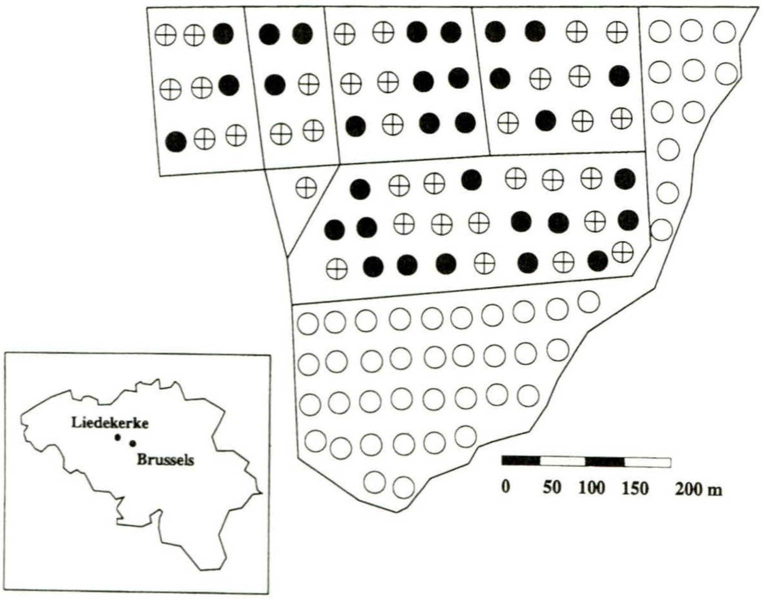


Figure 1.—*Distribution of the circular plots in the forest reserve of Liedekerke;* ● = *randomly selected plots inside the homogeneous part;* ⊕ = *non-selected plots inside the homogeneous part;* ° = *plots outside the homogeneous part.*

for the number of degrees of freedom. The Central Limit Theorem (CLT) states that a random sample n taken from any distribution approaches a normal distribution if n can increase without bound. Since this is usually not the case because most populations are finite, the CLT is arguable (Schreuder *et al.* 1993). Therefore, normality was tested by means of the Kolmogorov-Smirnov (Lilliefors) test considering a p-value of 0.05.

If the population is infinite or

$$\frac{N-n'}{N} \geq 0.95 \qquad (2)$$

where n' is the number of plots that were inventoried, then the second part of the denominator of (1) equals zero (Rondeux 1993).

RESULTS

Sample Size of the 1986 Inventory

The four data sets of stem number and basal area of all trees (dbh ≥ 2 cm and ≥ 5 cm) of the 1986 inventory in the 31 circular plots (= n') approach a normal distribution (Kolmogorov-Smirnov (Lilliefors) p > 0.2), so formula (1) could be applied. The total surface of the considered part of the forest reserve (12.9 ha) divided by the surface of a single circular plot (700 m^2) defines the population N = 183. This means that for a full inventory of the area, theoretically 183 circular plots are necessary. This population proved to be finite ((N-n')/N = 0.83 thus ≤ 0.95).

For each data set, sample size was calculated in function of a variety of accuracy and probability levels (degrees of freedom = ∞) (table 1).

Table 1.—*Sample size of the 1986 inventory for basal area and stem number, considering two dbh ranges and various levels of accuracy (E%) and probability (p) (expressed in numbers of circular plots and the corresponding percentage of the total surface of the homogeneous part of the forest reserve)*

Data set	Parameter	Dbh	Mean	E%	Number of circular plots p = 0.1	p = 0.05	p = 0.01	Percentage of total surface p = 0.1	p = 0.05	p = 0.01
		Cm	*m^2/ha*	*Percent*	- - - *Number* - - -			- - - *Percent* - - -		
1	Basal area	≥ 2	23.2	10	5.5	7.7	12.9	3.3	4.4	7.1
				5	20.1	27.3	42.5	11.5	15.3	23.6
				1	138.2	149.0	161.6	76.2	81.7	88.8
				0.1	182.4	182.6	182.8	100	100	100
2	Basal area	≥ 5	22.4	10	6.7	9.4	15.6	3.8	5.5	8.8
				5	24.1	32.4	49.6	13.7	18.1	27.4
				1	144.8	154.3	165.2	79.5	84.9	91.0
				0.1	182.5	182.7	182.8	100	100	100
		Cm	*Number /ha*	*Percent*	- - - *Number* - - -			- - - *Percent* - - -		
3	Stem number	≥ 2	1,844	20	6.4	9.0	14.9	3.8	4.9	8.2
				10	23.2	31.2	48.0	13.2	17.5	26.3
				5	67.1	82.6	107.4	37.3	45.5	59.2
				1	171.2	174.5	178.0	94.3	95.9	97.6
				0.1	182.9	182.9	182.9	100	100	100
4	Stem number	≥ 5	1,347	20	5.6	7.9	13.2	3.3	4.4	7.7
				10	20.5	27.8	43.3	12.1	15.3	24.1
				5	61.4	76.5	101.3	34.0	42.2	55.9
				1	169.6	173.3	177.3	93.2	95.4	97.6
				0.1	182.9	182.9	182.9	100	100	100

The required sample size needed to give a representative image of the forest reserve depends on the considered parameter.

For the basal area and the dbh range ≥ 2 cm, an inventory of 28 out of 183 plots or 15.3 percent of the total surface is sufficient for an accuracy level (E%) of 5 percent and a probability level of $p = 0.05$. In other words, in 9.5 cases out of 10, a random sample of 28 of the possible 183 plots results in an estimated mean basal area situated in an accuracy-interval of 5 percent around 23.2 m^2 per ha. For the dbh range ≥ 5 cm, the necessary plot density increases to 18.1 percent of the total surface, which makes the inventoried surface of 17 percent (31 plots) insufficient. In general, the area needed for the inventory of trees with dbh ≥ 5 cm is only slightly higher than for trees with dbh ≥ 2 cm (0.5 to 3.8 percent of the total surface). More than three-quarters of the total surface should be inventoried to reach an E% level of 1 percent, while an inventory of at least 3.3 percent of the total surface guarantees an E% level of 10 percent.

For the stem number, the sample size reaches 42.2 percent (dbh range ≥ 5 cm) and 45.5 percent (dbh range ≥ 2 cm) of the total surface for an E% level of 5 percent and a p-value of 0.05. Practically useful sample sizes for monitoring purposes are reached only at an E% level of 10 percent or more. The inventoried surface of 17 percent allows an E% level of 10 percent and a p-value of 0.05 for a dbh range ≥ 5 cm. This surface is slightly insufficient for a dbh range ≥ 2 cm. In contrast to the basal area, measuring trees with dbh ≥ 2 cm generally leads to a supplementary inventory area between 0.5 and 3.3 percent of the total surface in comparison with trees with dbh ≥ 5 cm.

Sample Size of the 1996 Inventory

The four data sets of 1996 (n' = 31 circular plots) of all trees showed a normal distribution (K-S (Lilliefors) $p > 0.2$ and K-S (Lilliefors) $p = 0.1697$ for the data set of stem number and dbh range ≥ 5 cm) so that formula (1) could be applied.

For each data set, sample size was calculated in function of a variety of accuracy and probability levels (degrees of freedom = ∞) (table 2).

Table 2.—*Sample size of the 1996 inventory for basal area and stem number, considering two dbh ranges and various levels of accuracy (E%) and probability (p) (expressed in numbers of circular plots and the corresponding percentage of the total surface of the homogeneous part of the forest reserve)*

Data set	Parameter	Dbh	Mean	E%	Number of circular plots			Percentage of total surface		
					p = 0.1	p = 0.05	p = 0.01	p = 0.1	p = 0.05	p = 0.01
		Cm	*m²/ha*	*Percent*	- - -	*Number*	- - -	- - -	*Percent*	- - -
1	Basal area	≥ 2	28.1	10	6.7	9.5	15.8	3.8	5.2	8.7
				5	24.3	32.8	50.2	13.3	18.0	27.5
				1	145.0	154.7	165.5	79.5	84.8	90.7
				0.1	182.5	182.7	182.8	100	100	100
2	Basal area	≥ 5	27.6	10	7.3	10.2	17.1	4.0	5.6	9.4
				5	26.1	35.1	53.3	14.3	19.2	29.2
				1	147.5	156.6	166.8	80.8	85.8	91.4
				0.1	182.6	182.7	182.8	100	100	100
		Cm	*Number /ha*	*Percent*	- - -	*Number*	- - -	- - -	*Percent*	- - -
3	Stem number	≥ 2	1,124	20	6.3	8.9	14.9	3.8	4.9	8.2
				10	23.0	31.1	48.0	12.6	17.0	26.3
				5	66.7	82.4	107.4	36.6	45.2	58.9
				1	171.1	174.5	178.0	93.8	95.6	97.6
				0.1	182.9	182.9	182.9	100	100	100
4	Stem number	≥ 5	979	20	7.8	10.9	18.2	4.9	6.0	10.4
				10	27.7	37.1	56.0	15.3	20.8	30.7
				5	76.2	92.3	116.8	42.2	51.0	64.1
				1	173.3	176.1	178.9	95.4	97.0	98.1
				0.1	182.9	182.9	183.0	100	100	100

Again, the sample size needed to give a representative image of the forest reserve proves to depend on the considered parameter.

The 1996 inventory of 31 plots is insufficient to be representative for the mean basal area of the forest reserve for an acceptable E% level of 5 percent and a probability level of p = 0.05. At least 18 percent (dbh range ≥ 2 cm) or 19.2 percent (dbh range ≥ 5 cm) of the total surface needs to be inventoried. The necessary sample size—2.7 percent and 1.1 percent, respectively—has increased in comparison with 1986. In general, the area needed for the inventory of trees with dbh ≥ 5 cm is only slightly higher than for trees with dbh ≥ 2 cm (0.2 percent to 1.7 percent of the total surface). The 1996 inventory is nevertheless sufficient for an E% level of 5 percent but with a lower probability level of p = 0.1; it is also sufficient for a lower E% level of 10 percent but with a higher probability level of p = 0.01.

Again, the sample size for stem number is generally much higher than for basal area. Thirty-one plots are just sufficient for an E% level of 10 percent and a probability level of p = 0.05, considering the dbh range ≥ 2 cm. Just as for the basal area, sample size has increased for the dbh range ≥ 5 cm in comparison with 1986 for the same accuracy. However, for the dbh range ≥ 2 cm, sample sizes have remained the same or decreased. In contrast to the 1986 inventory, measuring trees with dbh ≥ 5 cm requires a supplementary surface ranging from 0.5 to 5.8 percent of the total surface in comparison with trees with dbh ≥ 2 cm.

DISCUSSION

To obtain an accuracy level or interval of 5 percent of the mean basal area, a sample size of about 15 to 19 percent of the total surface of this particular forest reserve is needed (p = 0.05). Such an accuracy level is usually accepted and striven for (Zöhrer 1980). These plot densities seem to be higher than those that are commonly used in The Netherlands (10 percent) (Stuurman and Clement 1993) and most German states (10 to 12.6 percent) (Albrecht 1990, Althoff 1993), but are still meaningful for application. However, for the mean stem number and the same accuracy and probability level, sample size increases to an unpractical level of about half of the total surface. Even if the accuracy level is lowered to 10 percent, still more than 15 to 20 percent of the total surface needs to be inventoried. Kölling and Otter (1987) found a similar difference between both parameters concerning sample size (table 3).

Table 3.—*Accuracy level (E%) for the mean basal area and the mean stem number in function of sample size, considering a probability level of p = 0.05 (Kölling and Otter 1987)*

Sample size	**Accuracy level (E%)** **Basal area**	**Stem number**
Percent of total surface	*Percent*	*Percent*
4.0	9	24
5.8	9	21
10.2	5	19

Considering a sample size of around 5 percent, comparable accuracy levels of 20 percent for the mean stem number were found for both dbh ranges and inventory periods (p = 0.05) (tables 1 and 2). Also, for the mean basal area, a sample size of around 5 percent led to almost the same accuracy level of 10 percent for both dbh ranges and inventory periods (p = 0.05). On the other hand, raising the accuracy level to 5 percent resulted in a sample size of ± 1.5 to 2.0 times that found by Kölling and Otter (1987). The fact that the sample size for stem number is systematically higher than that for basal area may also have an ecological background. Young trees have a much higher influence on stem number than on basal area. The latter is mainly determined by mature and older trees and is less sensitive for young trees. The occurrence of young trees can be very variable due to dynamic processes in the forest ecosystem. This spatial variability, combined with the different sensitivity of both parameters for young trees, is reflected in the coefficient of variation, which is systematically higher for stem number than for basal area. Because the coefficient of variation is a principal component in formula (1), the same difference is expressed in the required sample size.

In general, doubling the accuracy level from 10 to 5 percent for the basal area and from 20 to 10 percent for the stem number increases the required sample size ± 3.5 times, for the same probability level. This practically confirms the general conclusion of Zöhrer (1980), who states that by quadrupling the sampled area the accuracy will be doubled. This conclusion is inherent to formula (1) and indicates homogeneity of the stand for a certain parameter (s% becomes very small so that factor 1/(E%)2 is the most influential). On the other hand though, doubling the accuracy level from 10 to 5 percent for the stem number increases plot density only ± 2.5 times, contradicting the homogeneity presumption.

Except for data set 3, the required sample size is systematically higher in 1996 than in 1986 (tables 1 and 2). This evolution is probably explained by the natural development of the forest ecosystem from a rather homogeneous regeneration phase to a more varied and complex forest structure and composition. This development is reflected in a higher coefficient of variation and thus in a higher required sample size.

CONCLUSION

The required sample size for achieving a certain desired accuracy or precision is very much dependent on the considered parameter, in this case basal area and stem number. This study indicates that specification of the parameter is necessary when dealing with representativeness and that generalization needs to be avoided. For these two parameters, it appears to be questionable that a representative image of the forest reserve can be obtained by sampling only 5 to 15 percent of the total surface. Even for this young forest, characterized by its large stem number of more than 1,000 trees per hectare, the necessary sample size is fairly high, especially considering the parameter stem number. Therefore, it can be expected that by applying such plot densities in forest reserves with a far lower stem number, this conclusion will be even more distinct. Moreover, due to dynamic processes of decreasing and increasing stem number and basal area, necessary sample size changes in time, which implies that a fixed number of plots always holds the risk not to meet the requirement of representativeness. The evaluation of the representativeness of each measured parameter after a forest reserve inventory seems to be indispensable. The calculation method applied in this study can serve as a useful tool.

ACKNOWLEDGMENTS

This research was financed by the Forestry Service (afdeling Bos & Groen) of the Flemish Community (AMINAL) and executed at the Laboratory of Forestry of the University of Ghent (RUG). Special thanks to L. Nachtergaele, L. De Keersmaeker, D. Maddelein, and J. Van Slycken for their helpful suggestions.

The authors thank the following people for reviewing this manuscript: Jurij Diaci, University of Ljubljana, Ljubljana, Slovenia, and Bart Muys, Catholic University of Leuven, Leuven, Belgium.

LITERATURE CITED

Albrecht, L. 1990. Grundlagen, Ziele und Methodik der waldökologischen Forschung in Naturwaldreservaten. Naturwaldreservate in Bayern, Schriftenreihe, Band 1. Bayerisches Staatsministerium für Ernährung, Landwirtschaft und Forsten, München, 220 p.

Althoff, B.; Hocke, R.; Willig, J. 1993. Naturwaldreservate in Hessen. Waldkundliche Untersuchungen, Grundlagen und Konzept. Mitteillungen der Hessischen Landesforstverwaltung, Band 25, Wiesbaden, 170 p.

Broekmeyer, M.; Szabo, P. 1993. The Dutch forest reserves programme. In: Broekmeyer, M.; Vos, W.; Koop, H., eds. European forest reserves. Wageningen: Pudoc Scientific Publishers: 75-85.

Broekmeyer, M.; Vos, W.; Koop, H., eds. 1993. European forest reserves. Proceedings of the European forest reserves workshop. Wageningen: Pudoc Scientific Publishers. 306 p.

Bücking, W.; Kätzler, W.; Lange, E.; Reinhardt, H.; Weishaar, H. 1986. Methods for documenting succession as developed and applied in natural forest reserves in southwest Germany. In: Fanta, J., ed. Forest dynamics research in western and central Europe. Wageningen: Pudoc: 265-274.

De Cuyper, B. 1993. An unmanaged forest-research strategy and structure and dynamics. In: M. Broekmeyer, M.; Vos, W.; Koop,H., eds. European forest reserves. Wageningen: Pudoc Scientific Publishers: 215-216.

Hocke, R. 1996. Niddahänge östlich Rudingshain, Waldkundliche Untersuchungen, Materialenband. Naturwaldreservate in Hessen 5/1, Hessische Landesanstalt für Forsteinrichtung, Waldforschung und Waldökologie, Gieben. 470 p.

Kätzler, W. 1984. Zur forstlichen Aufname der Bannwälder in Baden-Württemberg. Mitteilungen der Forstlichen Versuchs- und Forschungsanstalt Baden-Württemberg. 108: 123-130.

Kölling, V.; Otter, A. 1987. Waldkundliche Aufnahme von Naturwaldreservaten (am Beispiel des Naturwaldreservates Seeben, Forstamt Krumbach). Unveröff. Manuskript am Lehrstuhl für Landschaftstechnik. LMU München.

Koop, H. 1989. Forest dynamics, SILVI-STAR: a comprehensive monitoring system. Berlin, Heidelberg, New York, Tokyo: Springer-Verlag. 229 p.

Kramer, H.; Akça, A. 1982. Leitfaden für Dendrometrie und Bestandsinventur. Frankfurt 1982. 251 p.

Noirfalise, A. 1984. Forêts et stations forestières en Belgique. Les Presses Agronomiques de Gembloux, Gembloux. 235 p.

Pardé, J. 1961. Dendrométrie. Ecole Nationale du Génie rural, des Eaux et Forêts, Nancy. 350 p.

Richter, A.; Grossmann, H. 1959. Untersuchungen über Probekreisgrösse und Netzpunktdichte bei Holzvorratsinventuren. Arch. Forstwes. 8: 976-1016.

Rondeux, J. 1993. La mesure des arbres et des peuplements forestiers. Les Presses Agronomiques de Gembloux, Gembloux. 521 p.

Schreuder, H.T.; Gregoire, T.G.; Wood, G.B. 1993. Sampling methods for multiresource forest inventory. New York: John Wiley & Sons, Inc. 446 p.

Spurr, S.H. 1952. Forest inventory. New York: The Ronald Press Company. 476 p.

Stuurman, F.; Clement, J. 1993. The standardized monitoring programme for forest reserves in The Netherlands. In: Broekmeyer, M.; Vos, W.; Koop, H., eds. European forest reserves. Wageningen: Pudoc Scientific Publishers: 99-108.

Zöhrer, F. 1980. Forstinventur-Ein Leitfaden für Studium und Praxis. Hamburg 1980. 207 p.

Alternative Sampling Designs and Estimators for Annual Surveys

Paul C. Van Deusen

Abstract.—Annual forest inventory systems in the United States have generally converged on sampling designs that: (1) measure equal proportions of the total number of plots each year, and (2) call for the plots to be systematically dispersed. However, there will inevitably be a need to deviate from the basic design to respond to special requests, natural disasters, and budgetary fluctuations. Some simple methods for maintaining a flexible panel design and implementing a moving average estimator are discussed.

There are several practical and theoretical reasons why annual systems have recently gained support. Equal annual budgets and work loads are easier to support politically than the fluctuations that result from the traditional periodic approach. Field crew retention improves when there is assurance of regular work within a compact region. Cooperation between the appropriate federal and state agencies can be regularly fostered without the multiyear hiatus that occurred under the old system. Statistically, there is an opportunity to realize gains from incorporating models and time series analysis that didn't exist under the old system. Something analogous to double sampling (Fairweather and Turner 1983, Hansen 1990) is very natural with an annual system. It's natural to take the expensive measurements on some of the plots each year while simulating measurements on the remaining plots. If the simulated measurements are "good," then overall precision is improved or fewer measurements need to be taken. Trends can be detected with only a 1-year lag under an annual system, as opposed to a multiyear lag under the traditional system. Flexibility is generally greater under an annual system. When budgets decrease, the proportion of plots can be reduced. Likewise, increasing budgets can be accommodated by measuring a larger proportion of plots.

Two well-established annual forest inventory systems are being tested and implemented at this time by the USDA Forest Service. The original system, AFIS, was developed in Minnesota, and its younger cousin (SAFIS) is being implemented throughout the South. SAFIS was conceived as a simplification of AFIS based on systematically measuring an equal proportion of plots each year. The AFIS designers originally focused on keeping costs down and felt that disturbance-based plot sampling would yield efficiencies that would justify its theoretical complexity. As public support has grown for AFIS and SAFIS, the need for cost savings has diminished relative to the need for producing publicly accessible methods and data. However, circumstances will inevitably occur where the basic SAFIS design will need to be complicated, at least temporarily.

Natural disasters such as hurricanes or ice storms that affect large forested areas are usually followed by a demand for a special inventory to assess damage. Budgetary decreases may make it impossible to complete field work as planned, while increases may require doing more than originally planned. There is also a need for SAFIS and AFIS to converge on similar sampling designs and analysis procedures as annual systems begin to be implemented nationally. The Forest Service receives regular feedback from the public on the need for compatible inventory procedures across regions and plans to accommodate these requests. Therefore, methods should be developed for enhancing the original SAFIS design or, depending on your point of view, simplifying the AFIS design.

DESIGN MODIFICATIONS

Only some very simple variations on the basic sample design will be discussed. A rigid SAFIS design would measure an equal proportion of plots, say 20 percent, each year. One way to do this would be to allocate each plot to one of five panels, and then measure one panel per year. Therefore, each panel would be regularly measured at 5-year intervals. The problem with this approach is that a pure non-overlapping panel design will only have data from which to estimate 5-year growth intervals. Therefore, other estimates will depend on the models, since plot updates will be over intervals that are less than 5 years. Such estimates are not design-unbiased. It's worth noting that a pure moving average estimator would be practically design unbiased even with rigid panels. The good news is that this may not be a problem for at least 5 years, because plots will have different measurement histories when they first enter the annual system. For example, the State of Georgia had plots that had been measured from 1 to 4 years earlier when they began the annual system in 1998.

Principal Research Scientist, NCASI, Anderson Hall, Tufts University, Medford, MA, USA, Pvandeus@tufts.edu

A possible solution is to follow the basic SAFIS plan for 5 years. After that, simply reshuffle the panel assignments in such a way that no plot is remeasured more frequently than 3 years or less frequently than 10 years. This would still result in five panels and would be transparent to the users. It allows use of a moving average estimator and resolves the concern about having only 5-year growth intervals. It would make model calibration easier as well. To implement the reshuffling, one might consider creating clusters of five neighboring plots each; then do the reshuffling within each cluster to maintain systematic coverage in each panel.

The rigid SAFIS design can't deal with budgetary fluctuations with a five-panel system. This issue could be handled by creating "extra" panels. Suppose you create 10 panels instead of 5. As long as there are enough resources to measure 20 percent each year, measure 2 of the 10 panels per year, i.e., the extra panel labels don't serve any purpose. However, if the budget starts to fluctuate, consider only measuring one panel or increase to measuring three panels. This maintains a panel design that systematically covers the region. The "extra" panel concept is a device to allow more flexibility in the future or for states that don't need 20 percent coverage each year. One could implement and maintain a 10-panel system by creating clusters of 10 plots each. The panel assignments within the clusters could be reshuffled periodically to maintain a mix of measurement intervals as well.

ANALYSIS OPTIONS

Much has been written elsewhere about analysis options (Hansen 1990, Reams and Van Deusen 1998, Van Deusen 1996a). These options can be grossly categorized into two groups, those that require imputed (modeled) values and those that don't. Imputation methods include single imputation and multiple imputation (Rubin 1987, Van Deusen 1996a). Multiple imputation has the advantage of allowing for simple estimates of means and variances, while single imputation leads to complicated variance estimates and the temptation to use ad hoc approaches. Regardless, multiple imputation is no panacea, because the bias and variance characteristics of these estimates will ultimately depend on the quality of the imputed values.

Two imputation-free methods can be applied to annual systems. The first is based on the fact that each panel provides an independent random sample from the entire population. Therefore, each panel can produce estimates in the year it was measured independent of the other panels. The second method involves combining panels measured in different years using a moving average or time series methodology. Therefore, the second method might be called the moving average approach, but it actually encompasses a number of procedures. For example, one might consider variations on the Kalman filter (Kalman 1963), mixed estimators (Theil 1971), exponentially weighted moving average (EWMA) models, etc. Since this is likely to be an important analysis method for annual systems, I will present the details for a mixed estimation approach.

Mixed Estimator

The mixed estimator (Theil 1971) has certain advantages over the Kalman filter or ad hoc moving average approaches in the context of annual surveys. The Kalman filter tends to have a start-up period of several years where the influence of initial starting values may dominate the data. Likewise, moving average methods often call for pre-specified weights to be applied to each of the input data values. The mixed estimator has neither of these deficiencies, although it is closely related to the Kalman filter.

The proposed mixed estimator is based on an observation equation that relates the observed panel means to the unknown population mean,

$$y_t = \beta_t + e_t \qquad t=1,\ldots,T \qquad (1)$$

where y_t is the mean from the panel measured in year t and e_t is an error term with mean 0 and variance σ^2_t/n_t. Model (1) by itself leads to estimating the population mean from the sample mean at time t. The population variance, σ^2_t, can be estimated in the usual way from the sample data. A second model is required to describe the transition of the mean over time. The transition equation could also be used to incorporate imputed values (Van Deusen 1996b). The simplest transition equation results from the assumption that the mean follows a random walk over time,

$$\beta_t = \beta_{t-1} + v_t \qquad t=2,\ldots,T \qquad (2)$$

where v_t is an error term with mean 0, variance $p\sigma^2_t/n_t$ and T corresponds to the cycle length.

The mixed estimator (Theil 1971) provides a method for combining equations (1) and (2) to produce estimates of the population mean for times t=1,...,T along with a covariance matrix. More elaborate notation is required to allow for plots being measured for the first time or remeasured at any sample occasion. Sampling with partial replacement methods (Van Deusen 1989) can serve as a template for adding any sequence of remeasurements.

Equation (2) allows the true mean to vary quite freely over time. Therefore, a more restrictive transition equation might be in order such as,

$$\beta_t = 2\beta_{t-1} - \beta_{t-2} + v_t \qquad t=3,\ldots,T \tag{3}$$

Equation (2) is controlling the slope of the mean transition trend, whereas equation (3) controls the second derivative of the mean trend, which will lead to smoother transitions.

Matrix notation facilitates derivation of estimators. Let $Y=[y_1,\ldots,y_T]'$, $\mathbf{B}=[\beta_1,\ldots,\beta_T]'$ and $\mathbf{e}=[e_1,\ldots,e_T]'$. Then equation (1) can be written in matrix form as $\mathbf{Y=B+e}$. To do the same for equation (2), let $\mathbf{R}$ be a T-1 by T matrix of the form

$$R = \begin{bmatrix} -1 & 1 & 0 & \ldots & 0 \\ 0 & -1 & 1 & \ldots & 0 \\ \\ 0 & 0 & \ldots & -1 & 1 \end{bmatrix} \tag{4}$$

and let $\mathbf{v}=[v_2,\ldots,v_T]'$. Now equation (2) can be simply written in matrix form as $\mathbf{0=RB+v}$, where $\mathbf{R}$ performs the task of first-differencing the parameters in $\mathbf{B}$. Equation (3) can be accommodated by defining $\mathbf{R}$ as T-2 by T with each row containing the sequence (1 -2 1) and eliminating v_2 from $\mathbf{v}$. Now the observation and transition equations can be written in matrix form as

$$\begin{bmatrix} Y \\ 0 \end{bmatrix} = \begin{bmatrix} D \\ R \end{bmatrix} B + \begin{bmatrix} e \\ v \end{bmatrix} \tag{5}$$

where $\mathbf{D}$ is a design matrix of 0's and 1's that serves to match up the elements in $\mathbf{Y}$ with the appropriate parameter in $\mathbf{B}$. For the example being discussed, D is an identity matrix.

Now define $\Sigma=\mathrm{diag}(\sigma^2_1/n_1,\ldots,\sigma^2_T/n_T)$, the covariance matrix for the error vector $\mathbf{e}$. More generally, Σ would contain off-diagonal terms to account for covariances between remeasured plots. Likewise, the covariance matrix for $\mathbf{v}$ is $\mathbf{p}\Omega$, where Ω is a diagonal submatrix of Σ. Using this notation, the mixed estimator for $\mathbf{B}$ (Theil 1971) is

$$\hat{\mathbf{B}} = \left(D'\Sigma^{-1}D + \frac{R'\Omega^{-1}R}{p}\right)^{-1} D'\Sigma^{-1}Y \tag{6}$$

with covariance matrix

$$V(\hat{\mathbf{B}}) = \left(D'\Sigma^{-1}D + \frac{R'\Omega^{-1}R}{p}\right)^{-1} \tag{7}$$

The diagonal elements of $V(\hat{\mathbf{B}})$ provide the estimated variances for the population mean estimates for times t=1,...,T. As p increases, the influence of the transition equation diminishes. In fact, as $p\to\infty$ the mixed estimator is the same as obtaining independent estimates from each panel when Σ is diagonal. Confidence intervals around change estimates are also available since $V(\hat{\mathbf{B}})$ contains the necessary covariance terms. The assumption here is that finite population correction factors (FPCs) can be ignored, because forest sampling usually involves large total area relative to the sampled area.

Maximum Likelihood Estimation of Unknowns

The p-parameter can be estimated along with $\mathbf{B}$ by maximizing the appropriate joint distribution. Assuming that the error vectors, $\mathbf{e}$ and $\mathbf{v}$, from the observation and transition equations follow independent multivariate normal distributions, their joint likelihood can be written as

$$L \propto \frac{1}{2}\Big[\log(|\Sigma|) + (Y-B)'\Sigma^{-1}(Y-B) + \frac{1}{p}B'R'\Omega^{-1}RB + \log(|p\Omega|)\Big] \tag{8}$$

The maximum likelihood estimates are those that minimize L. Given our assumptions, everything is known in equation (8) except p. For the example application, no effort is made to find the maximum likelihood estimate for p.

EXAMPLE APPLICATION

The purpose of the example is to demonstrate the effect of the transition equations and the p-parameter with all else held constant. A data set was simulated for 5 years with annual means of 10, 30, 15, 18, and 22. The diagonal terms in Σ and Ω were all set to 1. Equation (6) was used to fit the mixed estimator to these data with the variance parameter set to p=1 under transition equation (2) (fig. 1a) and for transition equation (3) (fig. 1b). The analysis is repeated (fig. 2) with p=5 to demonstrate how larger p-values increase the flexibility of the model. Comparison of results from the two transition equations with common p shows that equation (3) leads to smoother trends. In a real application, the components of Σ would be estimated from the data and p should be the value that maximizes likelihood function (8).

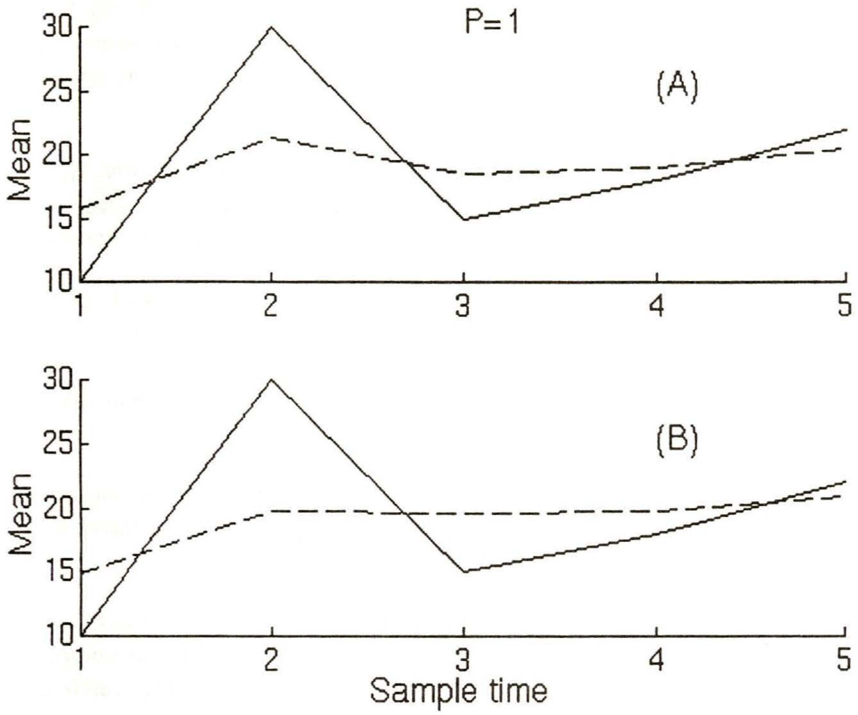


Figure 1.—*The mixed estimator (dash line) using (A) transition equation (2) and (B) transition equation (3) with p=1.*

CONCLUSIONS

Annual inventory systems based on systematic annual samples can provide timely and theoretically valid sample estimates. Minor variations from a rigid panel design have been discussed that can ensure that resulting estimates are practically design-unbiased. Estimation procedures based on imputation will likely come into use

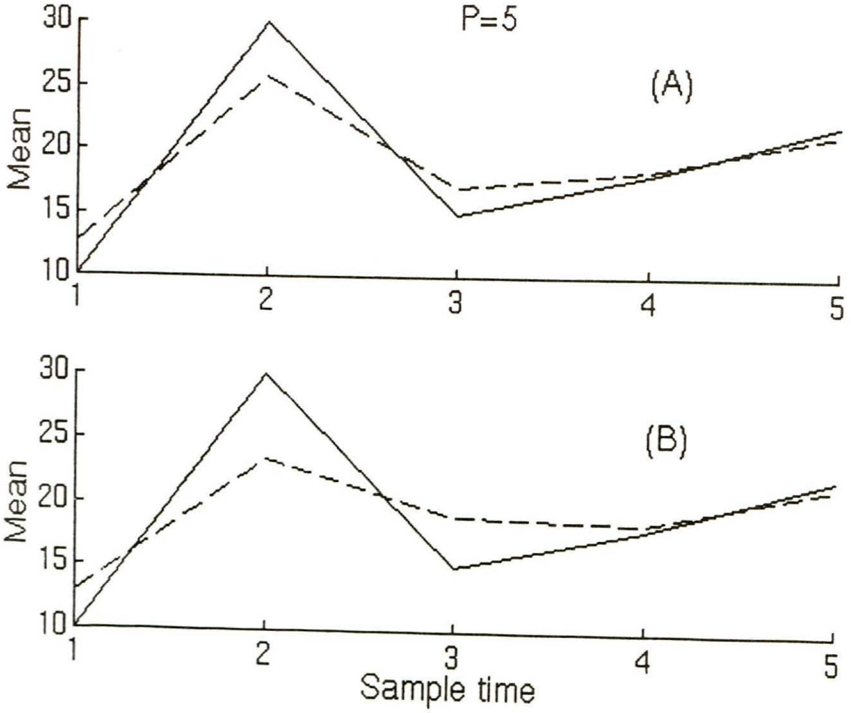


Figure 2.—*The mixed estimator (dash line) using (A) transition equation (2), and (B) transition equation (3) with p=5.*

after sufficient research is done to validate resulting estimates. As an alternative, variations of moving average estimators can provide practically design-unbiased estimates with well-defined variance estimators. In particular, a mixed estimator was developed here that is easy to apply.

ACKNOWLEDGMENTS

The following people reviewed this paper: Dr. Gregory A. Reams, USDA Forest Service, Asheville, NC, USA, and Dr. Francis A. Roesch, USDA Forest Service, Asheville, NC, USA.

LITERATURE CITED

Fairweather, S.E.; Turner, B.J. 1983. The use of simulated remeasurements in double sampling for successive forest inventory. In: Bell, J.F.; Atterbury, T., eds. Proceedings, Renewable resource inventories for monitoring changes and trends; 1983 August 15-19; Corvallis, OR: 609-612.

Hansen, M.H. 1990. A comprehensive sampling system for forest inventory based on an individual tree growth model. St. Paul, MN: University of Minnesota. Ph.D. dissertation.

Kalman, R.E. (1963). New methods in Wiener filtering theory. In: Bogdanoff, J.L.; Kozin, F., eds. Proceedings of the First symposium on engineering applications of random function theory and probability. Wiley: 270-388.

Reams, G.A.; Van Deusen, P.C. 1999. The southern annual forest inventory system.Journal of biology, Agriculture, and Environment Statistics.

Rubin, D.B. 1987. Multiple imputation for nonresponse in surveys. New York, NY: Wiley.

Theil, H. 1971. Principles of econometrics. New York, NY: Wiley.

Van Deusen, P.C. 1989. Multiple-occasion partial replacement sampling for growth components. Forest Science. 35(2): 388-400.

Van Deusen. P.C. 1996a. Annual forest inventory statistical concepts with emphasis on multiple imputation. Canadian Journal of Forest Research. 27: 379-384.

Van Deusen. P.C. 1996b. Incorporating predictions into an annual forest inventory. Canadian Journal of Forest Research. 26: 1709-1713.

Analysis of Natural Resource Inventory Data

Uncertainty Estimation of the Self-Thinning Process by Maximum-Entrophy Principle

Shoufan Fang and George Z. Gertner

Abstract.—When available information is scarce, the Maximum-Entropy Principle can estimate the distributions of parameters. In our case study, we estimated the distributions of the parameters of the forest self-thinning process based on literature information, and we derived the conditional distribution functions and estimated the 95 percent confidence interval (CI) of the self-thinning process for several tree species. The 95 percent CI indicated that the slope parameter of the so-called self-thinning law can be considered a random variable with a mean value of -3/2.

In ecology, the equation to describe the relationship between plant density and individuals' average biomass is considered the "self-thinning law" (or "self-thinning rule"). Its form is:

$$B = a \cdot D^{b} \quad \text{or} \quad \log(B) = A + b \cdot \log(D) \qquad (1)$$

where B is the average biomass of individual biobody, D is density. A [equaling to log(a)] and b are parameters. This relationship is called a "law" or "rule," not only because its parameter b has a quite stable value, but also because it can be derived from and interpreted by ecological theory (Drew and Flewelling 1977, Hozumi 1980, Zeide 1987). It is also widely applied in forest studies and management (Smith and Hann 1985; Valentine 1985, 1988; Weller 1987).

Many studies showed that the value of parameter b is close to -3/2 (White and Harper 1970, Hutchings 1979, Dean and Long 1985). However, some studies found that the estimated parameter b is not always around -3/2. It behaves like a random variable instead of a constant. Tolerance of a species, age, and site quality can vary the value of parameter b (Zeide 1985, 1987; Weller 1987; McFadden and Oliver 1988; Lonsdale 1990). The other factor that causes this parameter to change is climate, because tolerance property and site quality are both associated with weather conditions (Zeide 1985, 1987). The influence of those factors is usually not considered in a study. This can be considered to be interior uncertainty in studies of this law in specific forest ecosystems. On the other hand, sampling, measuring, grouping, and processing can cause uncertainty in data (Gertner 1991). This is exterior uncertainty. In studies of self-thinning law, the exterior uncertainty may have the same importance as the interior uncertainty, since sampling cannot easily guarantee that all the observations of a collected sample meet the closure assumption, which is the basis of the self-thinning law. Therefore, the estimated parameter b is impacted by both the interior and exterior uncertainty. Thus, it is necessary to be aware of uncertainty in studies of the relationship between average size and density since we cannot eliminate uncertainty by current techniques.

In studies of the self-thinning law, uncertainty will mainly exist in the distribution of average biomass. Whenever density is given, differences in species, climate patterns, and site quality will produce different total and average biomass. In data collection, measuring error will mainly occur in measurement of biomass, since it is much harder to measure than density. In Eq. 1, density is the independent variable and average biomass is the dependent variable. The estimated parameters will influence only biomass and not density. Therefore, uncertainty will be reflected by biomass. To estimate uncertainty of the self-thinning law is to estimate the behavior of biomass. The behavior of biomass is represented by the distribution of biomass at each density. It is almost impossible to directly estimate the distribution of biomass at all the possible densities, because density is actually a continuous variable. The way to estimate uncertainty in the self-thinning law is to estimate the uncertainty of parameters A and b first, and then estimate biomass.

Parameters A and b have been estimated in many studies. Those point estimates have been integrated to draw the histograms of A and b (Weller 1987). Since we know that species can cause variation in parameters A and b, it is not proper to estimate their distribution and analyze uncertainty without considering species. After grouping based on species, the numbers of the estimated parameters A and b are too small to estimate their distributions by traditional statistical estimation methods. Maximum-Entropy Principle (MEP) can estimate distribution of random variables based on insufficient information (Kapur 1989, Woodbury 1993). Applying MEP to

---

Ph.D. candidate and Professor of Biometrics, W503 Turner Hall, 1102 S. Goodwin Ave., Department of Natural Resources and Environmental Sciences, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA. This paper is based on a part of the Master's thesis of Shoufan Fang.

estimate the distribution of parameters A and b can be one way to analyze the uncertainty of the self-thinning law.

The purpose of this study is to demonstrate the usage of MEP in forestry study by applying it to estimate the distribution of parameters A and b with literature information and to estimate the distribution of biomass to indicate uncertainty in the self-thinning process.

ESTIMATION OF PARAMETERS' DISTRIBUTION BY MEP

Weller (1987) studied many cases of parameters A and b for several species. In his study, Weller took B as the biomass on unit area instead of individual average biomass in Eq. 1. With this change, the value of b should be close to -1/2 (Weller 1987). We take Weller's parameter A, b estimates (see table 1) as literature information in our study. With the data set, we computed the coefficient of correlation between parameters A and b. The coefficient of correlation was -0.045. It is very small. So, parameters A and b can be considered independent.

We estimated sample mean and interval for each species with the estimated A's in table 1. The sample means and intervals are listed in table 2. For parameter b, we assume that its mean is -0.5 and its interval is {-0.8, -0.2}. For convenience, b', the absolute value of b, was used in estimation. Following Laplace's principle of insufficiency, uniform distribution was selected as prior distribution of both A and b'. For species *Pinus taeda, Picea abies, Trifolium subterraneum, Erigeron canadensis,* and *Eucalyptus regnans*, the mean and midpoint are equal in each species (see table 2). According to MEP (Kapur 1989, Woodbury 1993), the joint posterior probability distribution function (p.d.f.) of A and b' is a uniform distribution:

$$f(\mathrm{A},\mathrm{b}') = \frac{1}{0.6(\mathrm{A}_2 - \mathrm{A}_1)} \qquad (2)$$

For the other species, the p.d.f. of A and b' is (Kapur 1989, Woodbury 1993):

$$f(\mathrm{A},\mathrm{b}') = \frac{-\beta\exp(-\beta \mathrm{A})}{0.6[\exp(-\beta \mathrm{A}_1) - \exp(-\beta \mathrm{A}_2)]} \qquad (3)$$

where β can be numerically solved as (Woodbury 1993):

$$\beta \approx \frac{3(\mathrm{A}_2 - \mathrm{A}_1 - 2\mu_A)}{2\mu_A^2}$$

Table 1.—*Estimates of parameters of self-thinning law (from Weller 1987)*

Species and case number	Intercept [log(a)]	Slope (-b)
Abies sacchalinsis		
(1)	1.71	2.786*
(2)	4.39	0.465
(3)	4.16	0.649*
Erigeron canadensis		
(1)	4.36	0.621*
(2)	5.70	1.038*
Eucalyptus regnans		
(1)	1.39	2.478*
(2)	3.44	1.066*
Lolium perenne		
(1)	4.80	0.427
(2)	4.20	0.245
(3)	4.33	0.544*
(4)	4.28	0.503
(5)	3.74	0.324
Trifolium subterraneum		
(1)	4.60	0.473
(2)	5.17	0.622
Beta vulgaris		
(1)	4.79	0.662*
(2)	5.12	0.692*
(3)	5.09	0.668*
(4)	5.22	0.649
(5)	5.30	0.648
(6)	6.39	1.335
(7)	9.93	2.304
Picea abies		
(1)	3.97	0.433*
(2)	3.90	0.422*
Pinus strobus		
(1)	3.34	1.116*
(2)	3.78	0.724*
(3)	3.44	0.954*
Pinus taeda		
(1)	4.21	0.305*
(2)	3.42	0.670*

*By Weller's analysis: the slopes are different from -1/2 at 0.05 level.

Table 2.—*Estimated distribution of parameter A for different species by MEP*

Species	Lower bound(A_1)	Upper bound(A_2)	Mean	β
Abies sacchalinsis	0.06	6.04	3.420	-0.098321
Beta vulgaris	3.16	11.59	5.976	0.526256
Erigeron canadensis	2.71	7.35	5.030	—*
Eucalyptus regnans	-0.26	5.09	2.415	—*
Lolium perenne	2.14	6.45	4.280	0.009826
Picea abies	2.25	5.62	3.935	—*
Pinus strobus	1.69	5.43	3.520	0.035833
Pinus taeda	1.77	5.86	3.815	—*
Trifolium subterraneum	2.95	6.82	4.885	—*

*In those species, their intercepts have uniform distribution.

The computed β values for different species is in table 2 and the estimated marginal distribution of parameter A for all the species are in figure 1.

Distribution Transformation

Assuming the distribution of parameters A and b are $f_1(A)$ and $f_2(b)$, respectively, and their joint distribution is $f(A,b)$, the distribution of biomass can be gained by using the following transformation.

Let $y_1 = A - b' \cdot \log(D)$ and $y_2 = b'$

where b'=-b, A and D have the same meaning as in Eq. 1, and y_1 equals the logarithm of biomass.

We can have:

$$A = G_1(y_1, y_2) = y_1 + y_2 \cdot \log(D) \quad \text{and}$$

$$b' = G_2(y_1, y_2) = y_2$$

and Jacobian J=1. Therefore, the joint distribution of y_1 and y_2 can be transformed by:

$$W(y_1, y_2) = f[G_1(y_1, y_2), G_2(y_1, y_2)]|J| \tag{4}$$

and the marginal distribution of y_1 is:

$$W_1(y_1) = \int W(y_1, y_2) dy_2 \tag{5}$$

$W_1(y_1)$ is the distribution of the dependent variable, log(B), in Eq. 1, if the joint distribution of y_1 and y_2 is integrable.

PROBABILITY DISTRIBUTION FUNCTION OF LOG(B)

Based on the posterior distribution of A and b', $W_1(y_1)$ can be gained by integration on y_2 for each type of distribution, since both types of joint distribution of A and b' are integrable. The area of the joint distribution of y_1 and y_2 can be divided into two to three different sections (see fig. 1). Integration was based on the boundary of each section under each relationship between log(D) and the intervals of parameters A and b'.

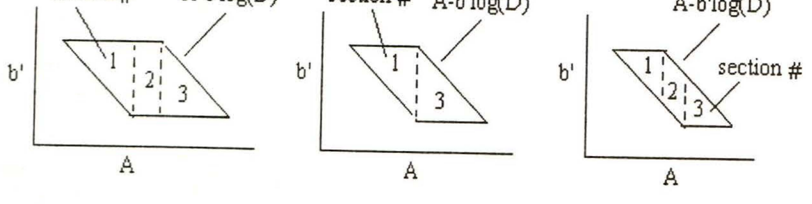


Fig. 1-a

Fig. 1-b

Fig. 1-c

Figure 1.—*The three integral sections of the joint distribution of* y_1 *and* y_2 *under different relationships between log(D) and the intervals of parameters A and b': Fig. 1-a.* $[0.6\log(D)]^2 < (A_2 - A_1)^2 + 0.6^2$, *Fig. 1-b.* $[0.6\log(D)]^2 = (A_2 - A_1)^2 + 0.6^2$, *and Fig. 1-c.* $[0.6\log(D)]^2 > (A_2 - A_1)^2 + 0.6^2$.

For Uniform Distribution of A and b'

For species *E. canadensis, E. regnans, P. abies, P. taeda,* and *T. subterraneum*, parameters A and b have joint p.d.f. of uniform expressed by Eq. 2. The transformed joint p.d.f. of y_1 and y_2 is:

$$W(y_1,y_2) = f[G_1(y_1,y_2),G_2(y_1,y_2)]|J| = \frac{1}{0.6(A_2 - A_1)} \tag{6}$$

And the marginal distribution of y_1 is :

$$W_1(y_1) = \int \frac{dy_2}{0.6(A_2 - A_1)} \tag{7}$$

When the relationships between A's interval and log(D) is different, the marginal distribution of y_1 will be different within different sections. The integrated generalized $W_1(y_1)$'s are listed in table 3-1.

For Exponential Distribution of A and b'

In species *L. perenne, B. vulgaris, A. sacchalinsis*, and *P. strobus*, parameters A and b' have exponential joint distribution (Eq. 3). The transformed joint p.d.f. of y_1 and y_2 is:

$$W(y_1,y_2) = f[G_1(y_1,y_2),G_2(y_1,y_2)]|J|$$

$$= \frac{-\beta \exp\{-\beta[y_1 + y_2 \log(D)]\}}{0.6[\exp(-\beta A_1) - \exp(-\beta A_2)]} \tag{8}$$

And the marginal p.d.f. of y_1 is :

$$W_1(y_1) = \int W(y_1,y_2)dy_2 \tag{9}$$

Just as with uniform distribution of parameters A and b', integration section determines y_1 's marginal p.d.f.. When the intervals of parameter A and log(D) have different relationships, the obtained $W_1(y_1)$'s are listed in table 3-2.

C. D. F. AND CONFIDENCE LEVEL OF LOG(B)

Fortunately, with different relationships between log(D) and intervals of parameters A and b', $W_1(y_1)$ has the same p.d.f. on Section 1 (or Section 3) when the joint distribution of A and b' is the same (see table 3). The difference of p.d.f. occurred in Section 2. Therefore, we can find out the relationship between confidence level and upper and lower bounds on y_1 's distribution. Let $2a$ be the confidence level, y_a and y_{1-a} be the lower and upper bounds of 1-$2a$ confidence interval, respectively. We will derive the relationships between confidence level and bounds based on the joint distribution of parameters A and b'.

For Uniform Distribution of A and b'

In table 3-1, the $W_1(y_1)$ of Section 1 is in the first row. Its corresponding cummulated probability distribution (C. D. F.) will be:

Table 3-1.—*The probability distribution function of log(B) for those species in which the parameters A and b' have uniform joint distribution*

Relationship	$W_1(y_1)$	Interval
$[0.6\log(D)]^2 < (A_2 - A_1)^2 + 0.6^2$	$W(y_1,y_2)[0.8 - \frac{(A_1 - y_1)}{\log(D)}]$*	$A_1 - 0.8\log(D) < y_1 < A_1 - 0.2\log(D)$
	$0.6 \cdot W(y_1,y_2)$	$A_1 - 0.2\log(D) < y_1 < A_2 - 0.8\log(D)$
	$W(y_1,y_2)[\frac{(A_2 - y_1)}{\log(D)} - 0.2]$	$A_2 - 0.2\log(D) > y_1 > A_2 - 0.8\log(D)$
	0	elsewhere
$[0.6\log(D)]^2 = (A_2 - A_1)^2 + 0.6^2$	$W(y_1,y_2)[0.8 - \frac{(A_1 - y_1)}{\log(D)}]$*	$A_1 - 0.8\log(D) < y_1 < A_1 - 0.2\log(D)$
	$W(y_1,y_2)[\frac{(A_2 - y_1)}{\log(D)} - 0.2]$	$A_2 - 0.2\log(D) > y_1 > A_2 - 0.8\log(D)$
	0	elsewhere
$[0.6\log(D)]^2 > (A_2 - A_1)^2 + 0.6^2$	$W(y_1,y_2)[0.8 - \frac{(A_1 - y_1)}{\log(D)}]$	$A_1 - 0.8\log(D) < y_1 < A_2 - 0.8\log(D)$
	$W(y_1,y_2)\frac{(A_2 - y_1)}{\log(D)}$	$A_2 - 0.8\log(D) < y_1 < A_1 - 0.2\log(D)$
	$W(y_1,y_2)[\frac{(A_2 - y_1)}{\log(D)} - 0.2]$	$A_2 - 0.2\log(D) > y_1 > A_1 - 0.2\log(D)$
	0	elsewhere

*$W(y_1,y_2)$ is the joint distribution of y_1 and y_2.

Table 3-2.—*The probability distribution function of log(B) for those species in which the parameters A and b' have exponential joint distribution.*

Situation	$W_1(y_1)$*	**Interval**
$[0.6\log(D)]^2 < (A_2 - A_1)^2 + 0.6^2$	$\frac{G_1(A_1, A_2, y_1)\exp(-\beta y_1)}{0.6\ln(D)[\exp(-\beta A_1) - \exp(-\beta A_2)]}$	$A_1 - 0.8\log(D) < y_1 < A_1 - 0.2\log(D)$
	$\frac{G_2(A_1, A_2)\exp(-\beta y_1)}{0.6\ln(D)[\exp(-\beta A_1) - \exp(-\beta A_2)]}$	$A_1 - 0.2\log(D) < y_1 < A_2 - 0.8\log(D)$
	$\frac{G_3(A_1, A_2, y_1)\exp(-\beta y_1)}{0.6\ln(D)[\exp(-\beta A_1) - \exp(-\beta A_2)]}$	$A_2 - 0.2\log(D) > y_1 > A_2 - 0.8\log(D)$
	0	elsewhere
$[0.6\log(D)]^2 = (A_2 - A_1)^2 + 0.6^2$	$\frac{G_1(A_1, A_2, y_1)\exp(-\beta y_1)}{0.6\ln(D)[\exp(-\beta A_1) - \exp(-\beta A_2)]}$	$A_1 - 0.8\log(D) < y_1 < A_1 - 0.2\log(D)$
	$\frac{G_3(A_1, A_2, y_1)\exp(-\beta y_1)}{0.6\ln(D)[\exp(-\beta A_1) - \exp(-\beta A_2)]}$	$A_2 - 0.2\log(D) > y_1 > A_2 - 0.8\log(D)$
	0	elsewhere
$[0.6\log(D)]^2 > (A_2 - A_1)^2 + 0.6^2$	$\frac{G_1(A_1, A_2, y_1)\exp(-\beta y_1)}{0.6\ln(D)[\exp(-\beta A_1) - \exp(-\beta A_2)]}$	$A_1 - 0.8\log(D) < y_1 < A_2 - 0.8\log(D)$
	$\frac{G_4(A_1, A_2, y_1)\exp(-\beta y_1)}{0.6\ln(D)[\exp(-\beta A_1) - \exp(-\beta A_2)]}$	$A_2 - 0.8\log(D) < y_1 < A_1 - 0.2\log(D)$
	$\frac{G_3(A_1, A_2, y_1)\exp(-\beta y_1)}{0.6\ln(D)[\exp(-\beta A_1) - \exp(-\beta A_2)]}$	$A_2 - 0.2\log(D) > y_1 > A_1 - 0.2\log(D)$
	0	elsewhere

*In $W_1(y_1)$, $G_1(A_1, A_2, y_1) = \exp[-0.8\beta\log(D)] - \exp[-\beta(A_1 - y_1)]$,

$G_2(A_1, A_2) = \exp[-0.8\beta\log(D)] - \exp[-0.2\beta\log(D)]$,

$G_3(A_1, A_2, y_1) = \exp[-\beta(A_2 - y_1)] - \exp[-0.2\beta\log(D)]$,

and $G_4(A_1, A_2, y_1) = \exp[-\beta(A_2 - y_1)] - \exp[-\beta(A_1 - y_1)]$.

$$P(Y_1) = \int_{-\infty}^{Y_1} W_1(y_1)dy_1 = \frac{1.667Y_1[A_1 - 0.8\log(D)] - 0.833\{[A_1 - 0.8\log(D)]^2 - Y_1^2\}}{0.8\log(D)(A_1 - A_2)}$$

$$A_1 - 0.8\log(D) < Y_1 < \min\{[A_1 - 0.2\log(D)], [A_2 - 0.8\log(D)]\}$$

After setting confidence level $2a$, the lower bound will be:

$$y_a = A_1 - 0.8\log(D) + \sqrt{1.2 \cdot a \cdot \log(D)(A_2 - A_1)}, \quad \log(D)>0 \tag{10}$$

The $W_1(y_1)$ of Section 3 is in the third row. Its corresponding C. D. F. will be:

$$P(Y_1) = 1 - \int_{Y_1}^{\infty} W_1(y_1)dy_1 = 1 - \frac{0.833\{[A_2 - 0.2\log(D)]^2 - Y_1^2\} - 1.667\{Y_1[0.2\log(D) - A_1] - [A_2^2 + 0.04\log^2(D) - 0.4A_2\log(D)]\}}{\log(D)(A_1 - A_2)}$$

$$A_2 - 0.2\log(D) > Y_1 > \max\{[A_1 - 0.2\log(D)], [A_2 - 0.8\log(D)]\}$$

Accordingly, the upper bound will be:

$$y_{1-\alpha} = A_2 - 0.2\log(D) - \sqrt{1.2 \cdot \alpha \cdot \log(D)(A_2 - A_1)}, \quad \log(D)>0 \tag{11}$$

For Exponential Distribution of A and b'

Based on the $W_1(y_1)$ of Section 1, the corresponding C. D. F. will be:

$$P(Y_1) = \int_{-\infty}^{Y_1} W_1(y_1)dy_1$$

$$= \frac{1.33[e^{\beta A_2}(1.25+1.25\beta A_1 - \beta\log(D)]}{\beta\log(D)(e^{\beta A_1} - e^{\beta A_2})} +$$

$$\frac{1.667\{e^{\beta[A_1+A_2-0.8\log(D)]} + Y_1\beta e^{\beta(A_2+Y_1)}\}}{\beta\log(D)e^{\beta Y_1}(e^{\beta A_2} - e^{\beta A_1})},$$

$$A_1 - 0.8\log(D) < Y_1 < \min\{[A_1 - 0.2\log(D)],[A_2 - 0.8\log(D)]\}$$

And the C. D. F. on Section 3 is:

$$P(Y_1) = 1 - \int_{Y_1}^{\infty} W_1(y_1)dy_1 = 1 - \frac{1.667}{\log(D)}\{\frac{e^{\beta A_1}}{(e^{\beta A_1} - e^{\beta A_2})}[\frac{1}{\beta} - A_2$$

$$+0.2\log(D)] - \frac{[e^{\beta[A_1+A_2-0.2\log(D)]} + Y_1\beta e^{\beta(A_1+Y_1)}]}{\beta e^{\beta Y_1}(e^{\beta A_1} - e^{\beta A_2})}\},$$

$$A_2 - 0.2\ln(D) > Y_1 > \max\{[A_1 - 0.2\log(D)],[A_2 - 0.8\log(D)]\}$$

Because the C. D. F.'s at both sides are complicated, it is very difficult to derive an explicit relationship between the confidence level and bounds. However, when a confidence level is given, both the lower and upper bound of the confidence interval can be obtained by numerical methods based on the two C. D. F.'s.

UNCERTAINTY OF THE SELF-THINNING PROCESS

A 95 percent confidence level was chosen to determine the bounds of log(B) at different densities for each species. The confidence area of each species is shown in figure 2. In a species, the self-thinning process described by each case from Weller (1987) was also drawn in figure 2. For the 28 cases from the nine studied species, the proportion of the cases that do not violate self-thinning law is quite high. In the cases from *P. taeda*, *P. abies*, *E. canadensis*, *T. subterraneum*, and *L. perenne*, their estimated self-thinning processes are totally covered by their corresponding 95 percent confidence area (see fig. 2). In Case 7 of *B. vulgaris* and Case 1 of *P. strobus*, self-thinning processes cannot be covered by the corresponding 95 percent confidence area when log(D) is larger than 3. In Case 1 of either *A. sacchalinsis* or *E. regnans*, the self-thinning process is outside the corresponding 95 percent confidence area. Of all the 28 cases, just 4 fail to follow the self-thinning law based on 95 percent confidence area. The proportion not supporting the self-thinning law is 14.3 percent. In 85.6 percent of the cases, the self-thinning law cannot be rejected.

CONCLUSION AND DISCUSSION

Maximum-Entropy Principle (MEP) provides an alternative to estimate the distribution of random variables with insufficient information. Using probability transformation, distribution and uncertainty of biomass can be obtained from the uncertainty of parameters A and b of the self-thinning law based on literature information. With uncertainty in nature, sampling, and parameter estimation method, parameter b of the self-thinning law should be a random variable instead of a constant. The estimated 95 percent CI areas of the studied species suggested that the mean value of b should be –3/2.

LITERATURE CITED

Dean, T.J.; Long, J.N. 1985. Response of self-thinning to artificially reduced levels of leaf area in monocultures of Trifolium pratense. Annals of Botany. 55: 361-365.

Drew, T.J.; Flewelling, J.W. 1977. Some recent theories in yield-density and their application to Monterey pine plantation. Forest Science. 23: 517-534.

Gertner, G.Z. 1987. Approximating precision in simulation projections: an alternative to Monte Carlo methods. Forest Science. 33: 230-239.

Gertner, G.Z. 1991. Prediction bias and response surface curvature. Forest Science. 37: 755-765.

Hozumi, K. 1980. Ecological and mathematical considerations on self-thinning in even- pure stands, 2: growth analysis of self-thinning. Botanical Magazine. 93: 149-166.

Hutchings, M.J. 1979. Weight-density relationships in ramet populations of clonal perennial herbs, with special reference to the -3/2 power law. Journal of Ecology. 67: 21-33.

Jaynes, E.T. 1957. Information theory and statistical mechanics. Physiological Reviews. 106: 620-630.

Lonsdale, W.M. 1990. Self-thinning rule: dead or alive? Ecology. 71: 1373-1388.

McFadden, G.; Oliver, C.D. 1988. Three-dimensional forest growth model relating tree size, tree number, and stand age: relation to previous growth models and to self-thinning. Forest Science. 34: 662-676.

Kapur, J.N. 1989. Maximum-entropy models in science and engineering. New York, NY: John Wiley and Sons.

Kullback, S. 1959. Information theory and statistics. New York, NY: John Wiley and Sons.

Schreuder, H.T.; Gregoire, T.G.; Wood, G.B. 1992. Sampling methods for multiresource forest inventory. New York, NY: John Wiley & Sons.

Smith, N.J.; Hann, D.W. 1985. A new analytical model based on the -3/2 power rule of self-thinning. Canadian Journal of Forest Research. 14: 605-609.

Ulrych, T.; Bassrei, A.; Lane, M. 1990. Minimum relative entropy inversion of 1D data with applications. Geophysical Prospect. 38: 465-487.

Valentine, H.T. 1988. A carbon-balance model of stand growth: a derivation employing pipe model theory and self-thinning rule. Annals of Botany. 62: 389-396.

White, J.; Harper, J.L. Correlated changes in plant size and number in plant populations. Journal of Ecology. 67: 21-33.

Figure 2.—*The estimated 95 percent CI of log(B) of each species and its individual cases. Fig. 2-a. legend of Figure 2, Fig. 2-b. species:* A. sacchalinsis, *Fig. 2-c. species:* B. vulgaris, *Fig. 2-d. species:* E. canadensis*; Fig. 2-e. species:* E. regnans, *Fig. 2-f. species:* L. perenne, *Fig. 2-g. species:* P. abies, *Fig. 2-h. species:* P. strobus, *Fig. 2-i. species:* P. taeda, *Fig. 2-j. species:* T. subterraneum.

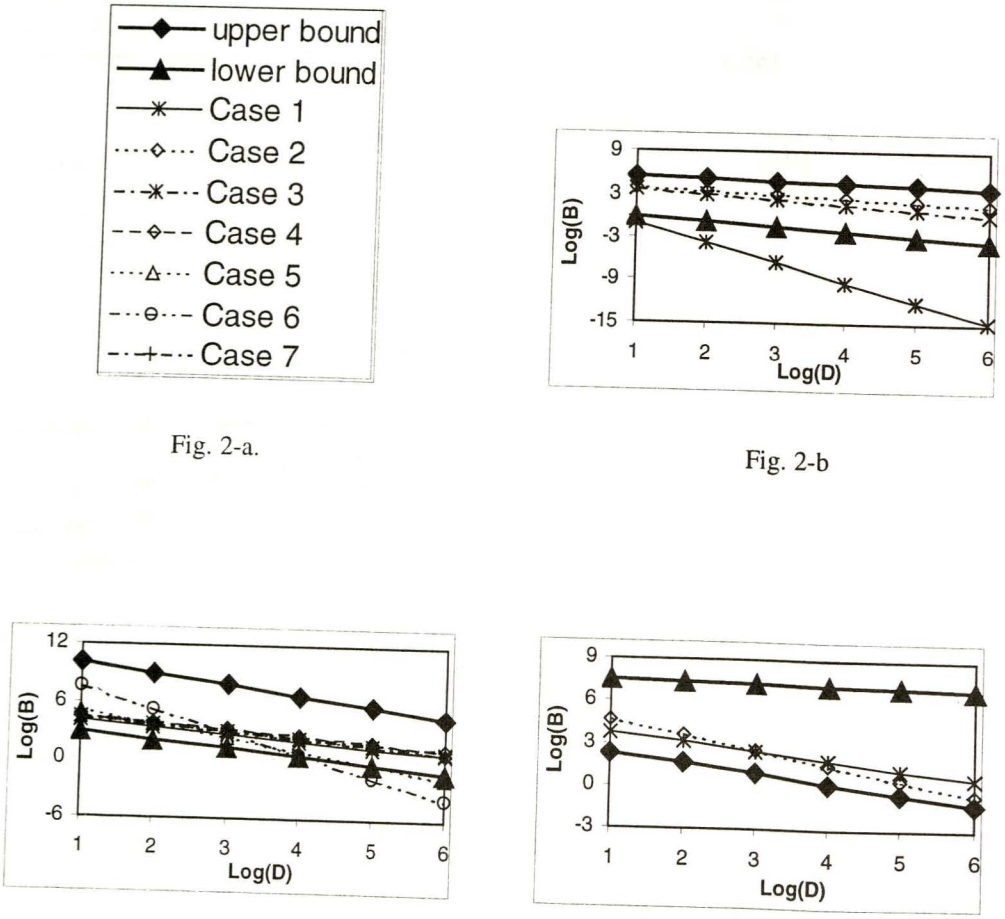


Fig. 2-a.

Fig. 2-b

Fig. 2-c

Fig. 2-d

(Figure 2 continued on next page)

(Figure 2 continued)

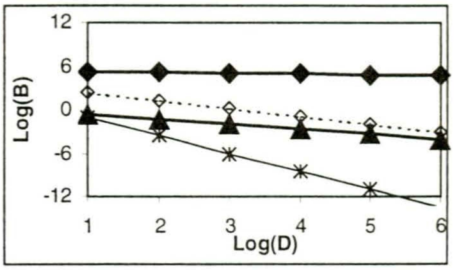


Fig. 2-e

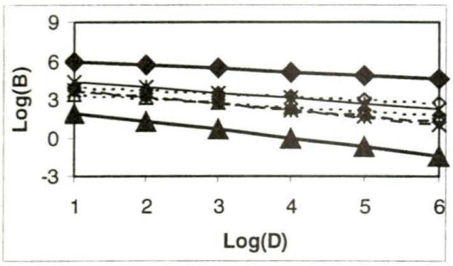


Fig. 2-f

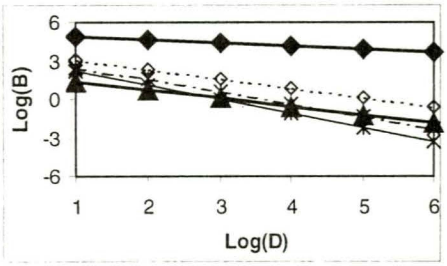


Fig. 2-g

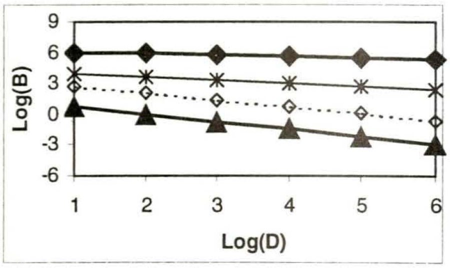


Fig. 2-h

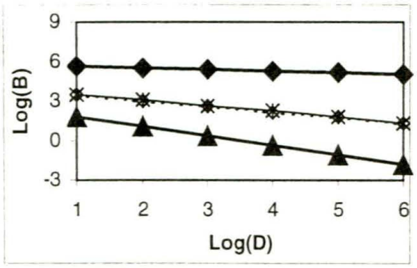


Fig. 2-i

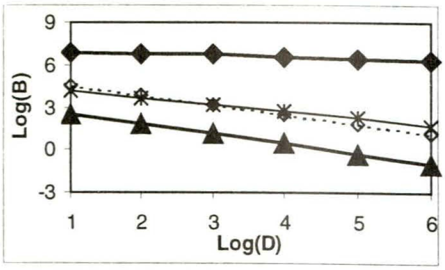


Fig. 2-j

Woodbury, A.D. 1993. Minimum relative entropy: forward probabilistic modeling. Water Resources Research. 29(8): 2847-2860.

Weller, D.E. 1987. A reevaluation of the -3/2 power rule of plant self-thinning. Ecological Monographs. 57: 23-43.

Zeide, B. 1985. Tolerance and self-tolerance of trees. Forest Ecology and Management. 13: 149-166.

Zeide, B. 1987. Analysis of the -3/2 power law of self-thinning. Forest Science. 33: 517-537.

Sources of Uncertainty in Annual Forest Inventory Estimates

Ronald E. McRoberts

Abstract.—Although design and estimation aspects of annual forest inventories have begun to receive considerable attention within the forestry and natural resources communities, little attention has been devoted to identifying the sources of uncertainty inherent in these systems or to assessing the impact of those uncertainties on the total uncertainties of inventory estimates. A brief overview of the annual forest inventory system under development for the North Central region is provided, sources of uncertainty within the required components are identified, and their magnitudes and impacts on Forest Inventory and Analysis (FIA) estimates are discussed.

Developers of annual forest inventory systems in the US generally agree that all such systems share requirements for several functions: (1) remote sensing; (2) an annual sample of measured plots; (3) a database of plot and tree information; and (4) a method for updating plot and tree information for plots that have not been measured in the current year. All these components are included in the annual forest inventory system that is being developed for the North Central region (fig. 1).

A brief overview of the annual forest inventory procedures under development for the North Central region describes the function of each component. Remote

---

Mathematical Statistician, USDA Forest Service, North Central Research Station, 1992 Folwell Avenue, St. Paul, MN, USA.

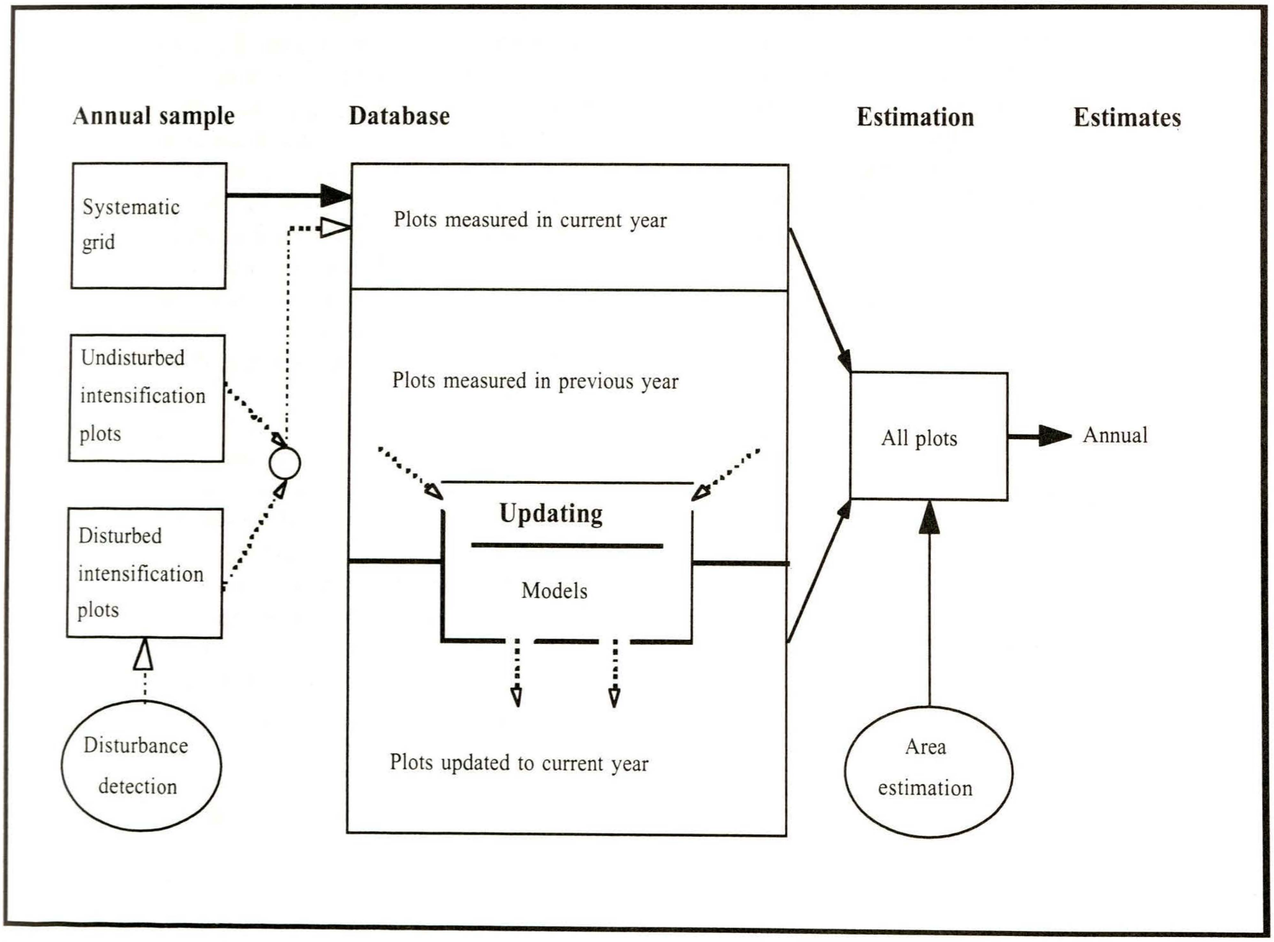

Annual sample
Database
Estimation
Estimates
Systematic grid
Plots measured in current year
Undisturbed intensification plots
Plots measured in previous year
Disturbed intensification plots
Updating
Models
All plots
Annual
Disturbance detection
Plots updated to current year
Area estimation

Figure 1.—*Annual forest inventories in the North Central region.*

sensing with satellite imagery is used to identify non-forested and broad strata of forested tracts, to estimate the area of these strata, to classify permanent Forest Inventory and Analysis (FIA) plots into one of these strata, and to determine the area within the strata represented by each plot. Second, an annual sample of plots is selected from two categories: first, a 20 percent sample of forested plots from a systematic grid of plots approximately uniformly distributed across each state, and second, additional non-grid plots selected for specific state-designated purposes. The set of plots selected from the grid is referred to as a single intensity inventory, and the measurement of these plots is funded by the USDA Forest Service. Some states, including Minnesota, Wisconsin, and Michigan, provide funds to measure additional plots for purposes such as increasing the precision of timberland estimates. The portion of the annual sample consisting of these supplemental plots is typically restricted to plots located on productive timberland. Plot and tree information is entered into a database where it is maintained and made accessible to users. Growth and mortality models are used to update the size and status of trees located on plots that are not measured in the current year. However, because the accuracy of the models is considered to be inadequate for trees on recently disturbed plots, first priority for the supplemental sample is given to plots that have experienced recent severe disturbance, primarily due to harvest. These disturbed plots are identified using remote sensing techniques that compare the two most recent sets of satellite imagery. Finally, FIA estimates for variables such as volume are obtained by summing across trees within plots to obtain plot-level estimates on a per acre basis, and then multiplying these plot-level per acre estimates by area expanders and summing across plots to obtain stratum, species, or regional estimates. The components of uncertainty that contribute to the uncertainty of the latter estimates are of primary interest for this study.

This paper is a preliminary report on a study that has three objectives: (1) to identify the sources of uncertainty associated with components of the annual forest inventory system used in the North Central region; (2) to estimate their magnitudes; and (3) to assess their impact on the overall uncertainty of annual forest inventory estimates.

REMOTE SENSING

Area Estimation

Remote sensing techniques are applied in forest inventories in the North Central region to estimate area and to classify plots into broad strata. These tasks are accomplished using remotely sensed data from two sources: satellite imagery from the Landsat Thematic Mapper (Bauer *et al.* 1994, Rack 1994, Moore and Bauer 1990, Hopkins *et al.* 1988) on an approximate 4-year cycle and recent low level aerial photography. The spectral band values from the satellite imagery are analyzed using digital methods to classify pixels into broad classes: cloud or cloud shadow, water, non-forest land, and one or more broad categories of forest land. The purpose of this level of classification is to estimate the overall forest area and to select plots for measurement that fall in forested tracts. The consequences of classification errors at this level are either to fail to include a forested plot in the sample or to include a non-forested plot in the sample. Inclusion of a non-forested plot reduces the precision of estimates, because such a plot does not contribute to estimates for the forested area. Exclusion of a forested plot from the sample generally does not reduce precision, because another forested plot will be selected in its place. However, such a failure may bias the overall volume estimate because the volume for the excluded plot was not available for inclusion in the sample that then includes non-random components.

Visual interpretation of low level photography is used to further stratify plots in forested tracts into strata that roughly correspond to categories related to land use, forest type, and size. The purpose of stratification at this level is to reduce the variances of final inventory estimates. Because of the labor intensity associated with photo interpretation, techniques for stratifying forested tracts using satellite data are also being developed, albeit for a smaller number of strata. For stratification to be beneficial, within-stratum variances must be smaller than the overall variance obtained without considering the stratification. Thus, classification errors at this level of stratification cause increases in the variances of final estimates. However, even with the finer resolution and larger number of strata obtained using photo interpretation, the relative magnitudes of the within-stratum variances for volume compared to the overall variance suggest that little benefit is being achieved with this approach (fig. 2).

The total area for each stratum, determined from remote sensing, is divided by the total number of plots in the stratum to obtain area expanders that indicate the area represented within a stratum by each plot. The sum over all plots within a stratum of the products of the per acre plot volume estimates and the corresponding area expanders produces a volume estimate for the stratum. Misclassification of plots at this level of stratification causes biased estimates of stratum area, inaccurate area expanders, and biased stratum estimates.

Disturbance Detection

A class of plots for which models are generally regarded as inadequate for predicting growth consists of plots that have experienced recent, severe disturbance. This class includes the approximately 1.5 percent of plots that are

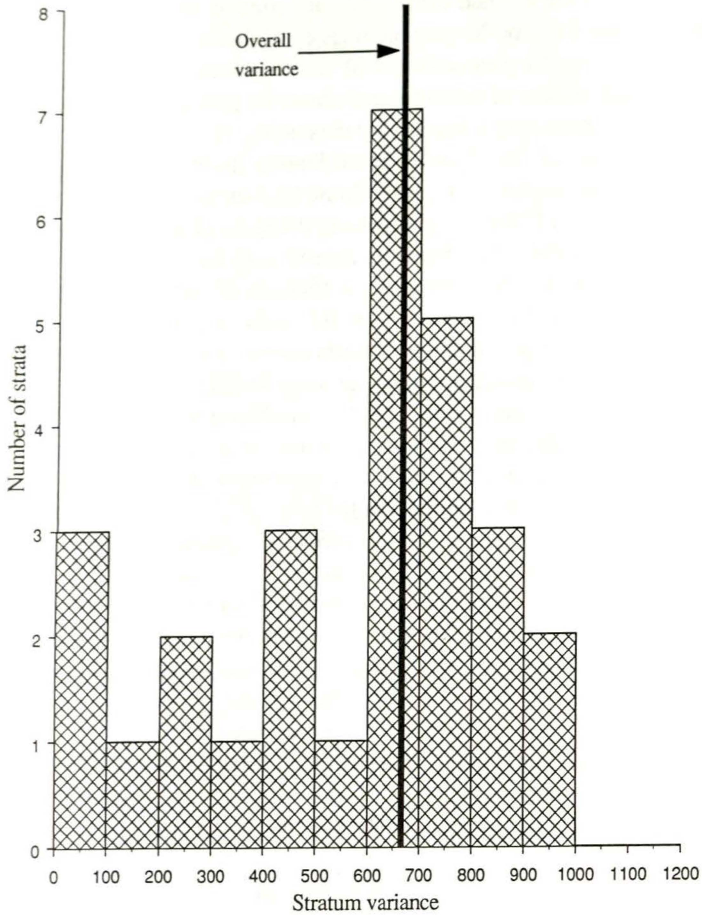


Figure 2.–*Results of stratification using photo interpretation.*

harvested in Minnesota annually. Digital disturbance detection is used to identify these plots so they can be selected for measurement as soon as regeneration has been established; for current applications this is approximately 5 years after disturbance. Digital disturbance detection consists of comparing the digital values for the Landsat Thematic Mapper spectral bands using computer-based algorithms. For each pixel, differences between the digital value for the two most recent sets of imagery are calculated and used to calculate values of an index that has been selected to be highly correlated with actual vegetation change on the ground. Based on their index values, pixels are classified into broad strata corresponding to vegetation gain, vegetation loss, and little vegetation change. Pixel-based maps representing disturbance classes are overlaid on the array of permanent FIA plots, and each plot receives a disturbance value.

The accuracy of disturbance detection has been partially assessed for plots whose loss of vegetation has been predicted to fall beyond one standard deviation of a mean index value (table 1). For predicted disturbance based on digital analysis of Landsat Thematic Mapper data at 4-year intervals and true disturbance based on examination of plot sheet comments recorded by field crews, 95 percent of plots predicted to be undisturbed were found to be actually undisturbed, while 69 percent of the plots predicted to be disturbed were found to have actually experienced disturbance. Because the purpose of disturbance detection is to identify plots for which growth

Table 1.—*Accuracy of digital disturbance detection*

Landsat TM status	Field observation		Total	Prediction success
	No change	Change		
	- - - - *no. plots*	- - - -		
No change	332	19	351	0.95
Change	53	116	169	0.69
Total	385	135	520	

models may be biased, there is little loss associated with failure to discover disturbance on plots where it was predicted to have occurred. Measurements for these plots are simply included with measurements for other undisturbed plots. However, failure to identify and measure a disturbed plot is much more serious, and although the cumulative error rate over the 4-year imagery cycle is only about 5 percent, it applies to approximately 96 percent of the plots. In such cases, pre-harvest volume, updated using the growth models, will erroneously be used for these plots rather than the minimal volume that will have regenerated in the approximately 5 years since harvest.

ANNUAL SAMPLE

The characterization of forest inventories as annual is based on the measurement of an annual sample of plots and the capability of producing annual FIA estimates, not on a complete annual inventory of all plots. FIA precision standards for the North Central region require a sampling intensity of one plot for approximately every 6,000 acres. To satisfy this requirement, a grid of hexagons, each approximately 5,900 acres in area, has been established by subdividing the hexagons established for the Forest Health Monitoring (FHM) program (Eagar *et al.* 1991, White *et al.* 1992). A permanent FIA field plot was either established or selected from existing plots to represent each smaller hexagon. The single intensity inventory, funded by the USDA Forest Service, consists of a 20 percent systematic sample from this grid each year. The State of Minnesota traditionally provides additional funding to increase the precision of inventory estimates for areas considered to be productive timberland. These supplemental plots are non-grid, permanent FIA plots on productive timberland selected according to two criteria: (1) plots that are predicted to have experienced substantial vegetation loss approximately 5 years ago are selected to determine how these plots have regenerated; and (2) a sample from the remaining non-grid plots that have not been predicted to have experienced harvest or other disturbance are either randomly selected or are selected to address specific issues such as the effects of drought, blow-downs, ice storms, or growth and mortality for particular species.

Three primary sources of uncertainty are of concern in the sampling component: among-plot sampling variability, within-plot sampling variability, and measurement error. Variability among plots cannot be controlled although its effects can be partially mitigated by stratification of plots to reduce its overall effects as previously discussed under remote sensing for area estimation. The term within-plot sampling variability is used to describe the variation in plot-level variables such as site index that are obtained via a sample. McRoberts (1996a) reported that site index estimates, obtained using age and height measurements from two or more dominant or codominant trees and site index curves, had coefficients of variation that ranged from 0.07 for 70-year-old trees on high site index plots to 0.13 for 50-year-old trees on low site index plots. The magnitudes of measurement errors for plot- and tree-level variables vary considerably depending on the variable measured. In a North Central Station study of field crew measurement error, each of nine field crews made standard FIA measurements on the same plot (McRoberts *et al.* 1994). For diameter, measured to the nearest 0.1 inch with a diameter tape, coefficients of variation ranged from 0.015 for small trees to 0.025 for large trees. Uncertainty in diameter measurements not only affects estimates of diameter and variables based on them such as basal area and volume, but for variable-radius plots it also affects tree expanders that indicate the number of trees per acre represented by each tree. Measurements of crown ratio, visually estimated as the ratio of living crown to height, ranged ±0.3 from the median. Frequently, these variables are selected as predictors in diameter growth models. A primary consequence of their uncertainties is to increase the uncertainty of growth predictions for trees on plots not measured in the current year (McRoberts 1996b). Finally, plot location errors may be relevant in this discussion, but they are expected to be minimized through application of global positioning systems.

UPDATING

Tree Variables

The Forest Inventory and Analysis program at the North Central Research Station currently uses the STEMS (Belcher *et al.* 1982) growth models to update plots and trees not measured in the current year. These regional models were developed from data collected primarily from research plots and have generally been accepted for application in the North Central region. If the updating procedure is sufficiently precise, the precision of the inventory estimates can be improved by inclusion of this large class of plots measured in previous years but without the adverse effects of using out-of-date information.

Although the STEMS models are generally accepted as adequately unbiased on a regional basis, there has been little analysis of their associated prediction uncertainty. The conclusions of a detailed report of recent simulation work in this area, reported in another session of this meeting (McRoberts *et al.* 2000), as they affect this discussion, are threefold: (1) although the uncertainty in diameter predictions may be large for individual trees, the effects are greatly attenuated for estimates at plot- and region-levels (fig. 3); (2) the effects of uncertainty in the model predictions, although relatively small on a regional basis, should not be ignored; and (3) the overall prediction uncertainty may possibly be reduced by excluding from the models some predictor variables, even though they

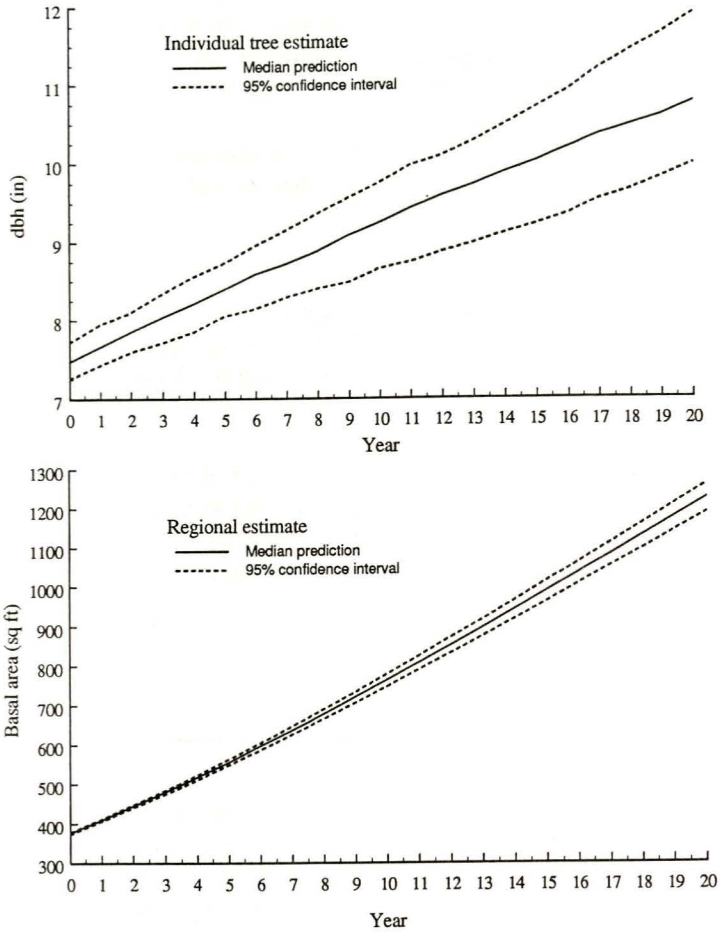


Figure 3.—*Uncertainty of predictions using STEMS diameter growth models based on 1,000 simulations that included uncertainty due to residual variability, dbh and crown ratio measurement errors, and site index sampling variability.*

significantly increase the quality of fit of the model to the calibration data.

Plot Regeneration

Although disturbances due to clearcuts can be detected with reasonable accuracy, the nature of the regeneration on these clearcut plots is usually uncertain for approximately 5 years after harvest. Thus, in Minnesota, field crews will not visit clearcut plots until approximately 5 years after harvest. However, because it is inappropriate to classify harvested plots as unstocked for 5 years, a procedure for estimating initial regeneration is being developed. While this procedure is being developed, regeneration of harvested plots is predicted to be in the same ground cover class as before harvest. This technique is regarded as a reasonable interim solution, but it generates uncertainty about the cover on harvested plots as will any technique that does not involve actual measurement of the plots.

DATABASE

The heart of annual forest inventories is the database of plot- and tree-level information. For all permanent FIA plots and for all trees on them, these data are entered into the database repository, updated when appropriate in subsequent years, and used to calculate FIA estimates. Although data entry and transcription errors contribute to the overall uncertainty in forest inventory estimates, no investigation of the magnitude or consequences of this source of uncertainty has been initiated at this time. The database is made accessible using increasingly user-friendly interfaces that allow users to conduct their own analyses.

CONCLUSIONS

The previous discussion on sources of uncertainty for annual forest inventories is summarized in table 2. Three conclusions can be drawn from the discussion: (1) additional analyses are required to quantify the uncertainty associated with the components of inventory systems and to quantify their impacts on the uncertainty of FIA estimates; (2) analyses should be undertaken to determine if the traditional variance reduction techniques such as stratification are producing the desired and expected benefits; and (3) careful analyses are required to properly determine the sources of uncertainty that are contributing most to the uncertainty of FIA estimates and

Table 2.—*Sources of uncertainty in annual forest inventories*

Component	Source of uncertainty	Magnitude	Impact	Comments
Remote sensing	Area estimation	Small	Small	
	Stratification	Small	Small	Perhaps little benefit
	Disturbance detection	Large	__?__	5% error on 96% of plots
Annual sample	Plot location	Small	Small	
	Sampling variability			
	Among plots	Large	Large	Unavoidable
	Within plots	Large	__?__	Contributes to model error
	Measurement error	Varies	__?__	Contributes to model error
Updating	Prediction uncertainty			
	Residual variability	Large	__?__	Less impact at regional level
	Parameter uncertainty	__?__	__?__	Less impact at regional level
	Propagation of uncertainty	Large	__?__	Less impact at regional level
	Regeneration	__?__	Small	Little volume involved
Data base	Recording	Small	Small	
	Data entry	Small	Small	
	User errors	__?__	__?__	

to develop techniques for eliminating or mitigating their adverse effects. Very simply, the time is upon us for detailed and thorough analyses of uncertainties in all inventories, whether annual or periodic, if we are to provide the public with defensible estimates of forest resources.

ACKNOWLEDGMENTS

The following people reviewed this manuscript: Gary Brand and Mark Hansen, USDA Forest Service, North Central Research Station, St. Paul, MN, USA, and H. Todd Mowrer, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA.

LITERATURE CITED

Bauer, M.E.; Burk, T.E.; Ek, A.R.; Coppin, P.R.; Lime, S.D.; Walsh, T.A.; Walters, D.K.; Befort, W.; Heinzen, D.F. 1994. Satellite inventory of Minnesota forest resources. Photogrammetric Engineering and Remote Sensing. 60: 287-298.

Belcher, D.W.; Holdaway, M.R.; Brand, G.J. 1982. A description of STEMS—the stand and tree evaluation and modeling system. Gen. Tech. Rep. NC-79. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 20 p.

Eagar, C.; Miller-Weeks, M.; Gillespie, A.J.R.; Burkman, W. 1991. Summary report: forest health monitoring - New England/Mid-Atlantic 1991. NE-INF-115-92. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Hopkins, P.F.; Maclean, A.L.; Lillesand, T.M. 1988. Assessment of Thematic Mapper imagery for forest applications under Lake States conditions. Photogrammetric Engineering and Remote Sensing. 54: 61-68.

McRoberts, R.E.; Hahn, J.T.; Hefty, G.J.; Van Cleve, J.R. 1994. Variation in forest inventory field measurements. Canadian Journal of Forest Research. 24: 1766-1770.

McRoberts, R.E. 1996a. Estimating variation in field crew estimates of site index. Canadian Journal of Forest Research. 26: 560-565.

McRoberts, R.E. 1996b. Monte Carlo simulations of nonlinear size-age relationships. In: Mowrer, H.T. *et al.*, eds. Spatial accuracy assessment in natural resources and environmental sciences: 2d international symposium; 1996 May 21-23; Fort Collins, CO. Gen. Tech. Rep. RM-277. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

McRoberts, R.E.; Holdaway, M.R.; Lessard, V.C. 2000. Comparing the STEMS and AFIS growth models with respect to the uncertainty of predictions. In: Hansen, M.; Burk, T., eds. Integrated tools for natural resources inventories in the 21st century: proceedings of the IUFRO conference; 1998 August 16-20; Boise, ID. Gen. Tech. Rep. NC-212 . St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 539-548.

Moore, M.M.; Bauer, M.E. 1990. Classification of forest vegetation in North-Central Minnesota using Landsat Multispectral Scanner and Thematic Mapper data. Forest Science. 36: 330-342.

Rack, J. 1994. Landsat TM data as a predictor of forest stand characteristics. Plan B Paper. St. Paul, MN: University of Minnesota, Department of Forest Resources. 25 p.

White, D.; Kimerling, J.; Overton, S.W. 1992. Cartographic and geometric components of a global sampling design for environmental monitoring. Cartography and Geography Information Systems. 19: 5-22.

Spatial Interpolation of Forest Conditions Using Co-Conditional Geostatistical Simulation

H. Todd Mowrer

Abstract.—In recent work the author used the geostatistical Monte Carlo technique of sequential Gaussian simulation (s.G.s.) to investigate uncertainty in a GIS analysis of potential old-growth forest areas. The current study compares this earlier technique to that of co-conditional simulation, wherein the spatial cross-correlations between variables are included. As in the earlier study, uncertainties were assessed across 500 independent spatial Monte Carlo realizations for each of three variables of interest (quadratic mean stand diameter, age of dominant and co-dominant trees, and percent canopy cover). Potential old-growth for the study area was estimated for each set of these perturbed realizations using a simple GIS analysis. An uncertainty histogram was created by adding the 500 realizations on a cell-by-cell basis. Results were compared using empirical confidence regions from the upper percentiles of the histogram for each study. For uncertainty assessment using these particular co-located spatial data, co-conditional simulation creates intuitively less desirable results, and does not appear to provide any advantage over independent realizations using s.G.s.. For other data sets, where all variables are not measured at each location, improvements may result.

The advent of inexpensive georeferencing through the use of global positioning systems (GPS), and visualization and manipulation of spatial data with geographic information systems (GIS) have greatly facilitated the application of geostatistical techniques to forestry. Moreover, the exact positioning of measurement locations within forest landscapes allows this point information to be analyzed on a continuum ("continuous model of spatial variation," c.f. Heuvelink, 1998) instead of averaging plot measurements within stand polygons that are assumed to be homogeneous ("discrete model of spatial variation," ibid.). Geostatistical techniques take advantage of spatial auto-correlation between variables measured at multiple locations, as quantified by the variogram (Isaaks and Srivastava 1989). To obtain unbiased estimates at intermediate unmeasured points, the model variogram is then used in the kriging process to determine the minimum variance weighted linear combinations of measured values from nearby locations. Sequential Gaussian simulation (s.G.s.) (Deutsch and Journel 1992) calculates the kriging mean and variance at each unmeasured location, and draws a random deviate from the resulting distribution to simulate the value at that point. Mowrer (1994) applied sequential Gaussian simulation to estimate forest crown cover uncertainties for propagation through raster-based GIS. Subsequently, Hershey *et al.* (1995) compared ordinary kriging, indicator kriging, and s.G.s. for mapping tree species distributions across the State of Pennsylvania. In 1997, Mowrer applied the s.G.s. process to create independent realizations for three input variables (quadratic mean diameter, mean age of dominant and co-dominant stems, and percent crown cover). A simple GIS analysis demonstrated the propagation of uncertainties from interpolation of plot location data on estimates of potential old-growth stands. The results of 500 realizations for each variable were propagated through the GIS analysis, and the results were added on a cell-by-cell basis to create an uncertainty surface for the resulting old-growth areas.

Cokriging (Carr *et al.* 1985) may improve the estimation process over kriging by including cross-correlations. This enabled the development of co-conditional simulation (Carr and Myers 1985), which first creates independent realizations across grids for each variable of interest, and then uses cokriging to include the auto- and cross-correlations between variables in the conditioning process. The current study used the Carr and Myers (1985) program COSIM, with modifications, to repeat the process from the earlier s.G.s. study. For brevity sake, the term co-simulation will be used in the subsequent discussion to mean co-conditional simulation. The goal of the current study is to determine if the inclusion of spatial cross-correlations improves estimates with respect to the earlier analysis.

METHODS

The data for the analysis consisted of measurements on eighty-two 1/50-acre georeferenced plots distributed across a 300-acre subalpine watershed on the Fraser

---

Research Forester (Mensuration), USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA.

Experimental Forest, Fraser, CO, USA. All stems greater than 1 inch diameter at 4-1/2 feet above the ground were measured and cored through the pith for age. Percent crown cover was calculated from two perpendicular crown radii on each tree. An extensive description of data collection techniques is provided in Mowrer (1997). The current analysis consisted of four separate steps: (1) estimation of the variogram and cross-variogram model structure from the georeferenced plot data; (2) modification of the COSIM program and creation of 500 Monte Carlo cross-correlated realizations each, for quadratic mean diameter (q.m.d.) and age of dominant and co-dominant trees, and, separately, 500 independent realizations for percent crown cover; (3) repetition of the GIS analysis for each of the 500 sets of realizations of input values, creating 500 realizations of potential old-growth locations for the analysis area; (4) creation of empirical confidence regions and comparison to the earlier analysis.

Variogram Modeling

For all pairs of data values (v_i, v_j) of variable $\boldsymbol{v}(v_1, v_2, \ldots, v_n)$ separated by directed vector $\mathbf{h}_{i,j}$, the number of which is denoted N(h), the *sample variogram* is calculated over all (i,j) data pairs separated by distance **h**, using the following equation:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{(i,j)|h_{i,j}=h}^{N(h)} (v_i - v_j)^2 .$$

When calculating a variogram from the sample data, a fixed increment to **h** is selected to maximize the structure in the variogram. This distance increment is usually called the lag spacing. Thus, the variogram value from the above formula is calculated for increasing increments of **h** reflecting larger and larger distances between v_i and v_j. The sample variogram is shown by dots in individual variograms of the matrix in figure 1. Variogram values ($\gamma|h|$) are plotted on the vertical axes, while the horizontal axes measure the magnitude of **h**. The *model variogram* is developed through the selection of one of several positive definite model forms (e.g., exponential, spherical, Gaussian, and power function). Positive definiteness is necessary to ensure the uniqueness of the kriging and cokriging results, discussed below. The selected variogram model form is then fitted (visually and mathematically) to the structure of the sample variogram, by varying the nugget, range, and sill parameters for the model (Isaaks and Srivastava 1989, Goovaerts 1996). Interactive variogram estimation software developed by Pannatier (1996) was used to calibrate the variograms for the current study.

The model forms for the three variograms (model type, range, nugget, sill, and isotropy) were maintained from the previous analysis to maximize comparability. Thus, because the quadratic mean diameter and age variogram models were exponential, their cross-variogram must be exponential, also. The equation for the exponential model (Pannatier 1996) is:

$$\gamma(h) = c\left[1 - \exp\left(-\frac{3h}{a}\right)\right]$$

Where *a* is the *range* parameter, the distance at which the average squared difference values reach a plateau and no longer increase. The *sill*, *c*, is the maximum variogram value on the vertical axis for this asymptote. A *nugget effect*, if it were present, would be indicated by a vertical model discontinuity at zero. The crown cover variogram model was maintained as spherical. The equation for the spherical model (Pannatier 1996) is:

$$\gamma(h) = \begin{cases} c\left(1.5\frac{h}{a} - 0.5\left(\frac{h}{a}\right)^3\right) & \text{if } h \le a \\ c & \text{otherwise} \end{cases}$$

The model variograms are shown by solid lines in the individual variograms in figure 1.

Cross-Variogram

For all pairs of data values of variable $\mathbf{u}$ ($u_1, u_2, \ldots, u_n$) and of variable $\boldsymbol{v}$ ($v_1, v_2, \ldots, v_n$) separated by directed vector $\mathbf{h}_{i,j}$, the number of which are denoted N(h), the sample cross-variogram is calculated from the following equation:

$$\gamma_{uv}(h) = \frac{1}{2N(h)} \sum_{(i,j)|h_{i,j}=h}^{N(h)} (u_i - u_j)\cdot(v_i - v_j).$$

The model cross-variogram is fitted to the sample cross-variogram in the manner described above for the variogram. In the current study, a cross-variogram for q.m.d. and mean plot age of dominant and co-dominant trees was calculated for use in the subsequent cokriging process in COSIM.

Simply stated, the idea of including cross-correlations in spatial analyses can be likened to explicit estimation of off-diagonal elements in the multivariate correlation or covariance matrix in classical statistics, instead of assuming independence (e.g., that off-diagonal elements are zero). In the geostatistical case, the diagonal elements of the spatial variogram matrix are more commonly referred to as spatial auto-correlations and are estimated by the variogram, while the off-diagonal elements are the cross-variograms. Using Moran's bivariate spatial statistic permutation test (Czaplewski and Reich 1993), age of dominant and co-dominant trees was found to be significantly spatially cross-correlated with q.m.d. Figure 1 displays the variogram matrix for the current analysis, with the cross-variogram for age of dominant and co-dominant trees and q.m.d. as the off-diagonal element from the variograms for these two variables. Percent crown cover is spatially independent of the others, and thus is represented by the single variogram on the diagonal. In general, one must estimate $n(n-1)/2$ cross-variograms for n variables, because the variogram matrix is symmetric. Certain rules must be followed in determining the model structure of cross-variograms, to ensure that the overall structure remains positive semi-definite (Goovaerts 1997). This can make cross-variogram estimation for more complex models a formidable task.

Cokriging

Now consider for $\boldsymbol{u}$ ($u_1, u_2, \ldots, u_n$) and $\boldsymbol{v}$ ($v_1, v_2, \ldots, v_m$), that m may be greater than or equal to n. In this case, $\boldsymbol{u}$ is considered the primary variable of interest, and $\boldsymbol{v}$ the secondary variable. The additional values of $\boldsymbol{v}$ for which values of $\boldsymbol{u}$ are not measured may improve the estimates of $\boldsymbol{u}$ at all estimated locations. For each estimation location, $\hat{u}$, the value to be estimated is obtained from the minimum variance weighted combination of the values at

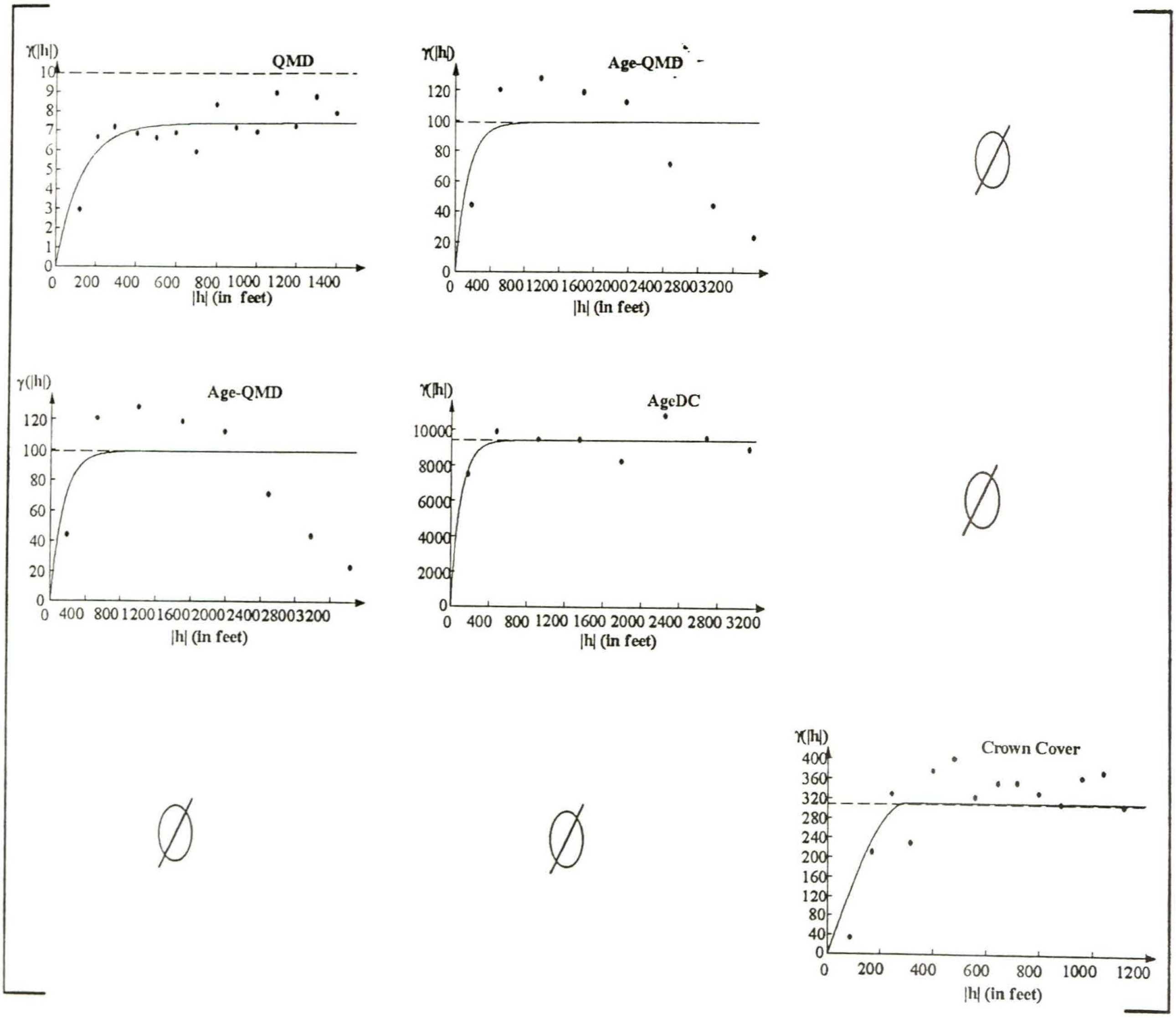


Figure 1.—*Variogram matrix, with the variograms for quadratic mean diameter (q.m.d.), age of dominant and co-dominant trees (AgeDC), and percent crown cover across the diagonal, and the cross-variogram for age and quadratic mean diameter (crown cover is considered to be independent). The vertical axes measure the variogram value* $(\gamma|h|)$ *for increasing distance between sample locations (in feet) along the horizontal axis. The sample variograms are shown by dots and the model variograms by solid lines. Note that the overall matrix for variograms and cross-variograms is symmetric.*

nearby points. This estimation process and the necessary constraints on the values of the weights ($a_1, a_2, \ldots, a_n$) and ($b_1, b_2, \ldots, b_m$) are as follows:

$$\hat{u} = \sum_{i=1}^{n} a_i \cdot u_i + \sum_{j=1}^{m} b_j \cdot v_j$$

where,

$$\sum_{i=1}^{n} a_i = 1, \ \sum_{j=1}^{m} b_j = 0.$$

The cokriging estimator was used in the COSIM program as described in the next section.

COSIM Computer Program

The COSIM computer program developed by Carr and Myers (1985) first creates a grid of random deviates through a non-conditional Monte Carlo simulation process called "turning bands." The grids (one for each variable) are then "conditioned," or adjusted to the spatial correlation structure described by the variograms and cross-variograms using the cokriging algorithm.

Non-conditional Simulation

The first step of the non-conditional part of the COSIM program is the creation of standard normal unidimensional random vectors with a given spatial correlation. Each vector is split up into a number of line segments of equal length, each assigned a standard normal random value. This random value is then assigned to a three-dimensional band, defined by planes perpendicular to the end points of each of these short line segments along the vector. Fifteen of these vectors are created, along the lines connecting midpoints of opposite edges of a regular icosahedron (a 20-sided figure, each side consisting of an equilateral triangle). These 15 vectors therefore pass at equal angles through the center of a sphere, which is the center point for the simulated area. The vectors are simulated in five groups of three. An initial set of three vectors is rotated (by way of matrix multiplication) through five consecutive sequences to create the requisite 15 vectors, each with their associated bands of random values, thus the term "turning bands."

A user-specified grid is established that passes through the center of the sphere. The random contribution from each band passing through the node of each cell in this grid is summed to provide the random deviate for that grid cell, thus completing the Monte Carlo portion of the simulation. A linear transformation is then used to create independent realizations with the same overall mean and variance as the original data. (Readers interested in a more detailed explanation of the non-conditional portion of this simulation are referred to Journel and Huijbregts (1978, p. 498.)) In COSIM, this process is repeated independently for each variable in the simulation (in the current analysis, two: quadratic mean diameter and mean age of dominant and co-dominant stems).

Cokriging

Cokriging is then used to give these independent realizations the same overall spatial structure as the original data, reflected in the variograms and the cross-variograms. As described above, the variograms and cross-variograms are used in the cokriging process to determine the minimum variance linear combination of weights for the conditioning data. A weighted moving average of conditioning data (the actual values of quadratic mean diameter and mean age at nearby plot locations) is thereby used to estimate values at unmeasured locations on the grid. This same set of weights is also applied to the random deviates (created in the step above) closest to the location of each conditioning datum. Thus, the COSIM program creates two estimates for each cell in the grid: the cokriging estimate and a second estimate created by applying the same set of weights to the set of simulated random deviates closest to each data location. To create the conditioned (spatially correlated) random deviate at each unmeasured grid cell location, the latter estimate was subtracted from the original (independent) random value for that grid cell, and the cokriging estimate added to the result.

COSIM Program Modifications

It was necessary to modify the COSIM program to accept the exponential variogram and cross-variogram models. Fortunately, Journel and Huijbregts (1978) derived formulae for the exponential variogram model that could be used as a theoretical basis for modifying the FORTRAN code in COSIM for the exponential models. The program was then run to create 500 spatially correlated realizations for these two variables, a process taking approximately 44 hours on a 400 MHz. personal computer. (By comparison, 500 realizations with the Deutsch and Journel (1992) s.G.s. program takes approximately 38 minutes on the same machine.) The original COSIM model was also run to create 500 independent realizations using a spherical variogram model for crown cover.

GIS Analysis

As mentioned above, the GIS analysis followed the same procedure as that outlined in Mowrer (1997). The goal of the analysis was to delineate areas that simultaneously satisfied three sets of conditions: quadratic mean stand diameter greater than 10 inches at breast height (4.5 feet above the ground), average age of dominant and co-dominant trees greater than 220 years, and percent crown cover greater than 40 percent. The study area was divided into a grid of 30-foot square cells: 116 in the north-south direction, and 160 in the east-west direction. Cells outside the delineated watershed polygon were deleted from the analysis. Each of 500 sets of three realizations (for quadratic mean diameter, age, and percent crown cover) from the co-simulation process was used to initialize the GIS analysis. For comparison, one realization for age from the current COSIM process is shown in figure 2a, and one realization for age from the s.G.s. process is shown in figure 2b. The GIS analysis created binary masks for each realization, whereby cells satisfying the previous criteria were given a value of one, and other cells were given a value of zero. By multiplying the binary cell values for these three images on a cell-by-cell basis, those cells with a resulting value of one would represent an area where estimated conditions satisfied the three criteria simultaneously. Otherwise a zero cell value would result. Summing the 500 output images resulted in an "uncertainty image" where the absolute number in each cell reflected the level of certainty of old-growth occurrence. These overall uncertainty images, resulting from the current co-simulation process and the previous s.G.s. process are shown in figures 3a and 3b, respectively. Figure 4 shows a comparison of the average cumulative variance across both the co-simulation and the

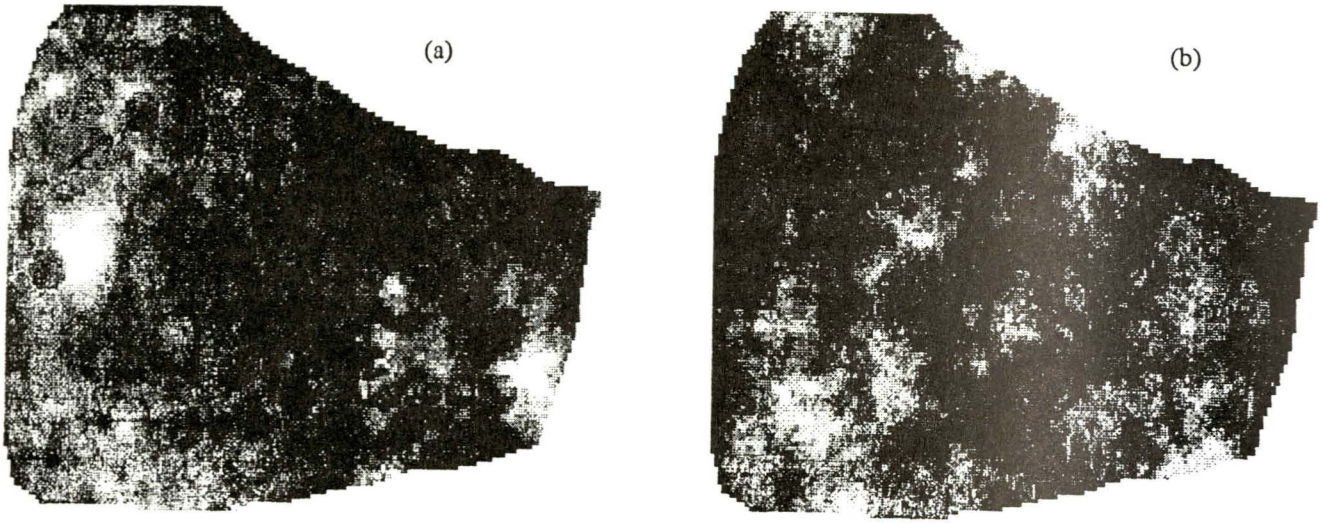


Figure 2.—*A single realization for age of dominant and co-dominant trees on the sample watershed from the conditional co-simulation program (a), and from the sequential Gaussian simulation program (b). Note striations across figure (a) and definite circles at sampled points. Darker gray-tones indicate higher values for age.*

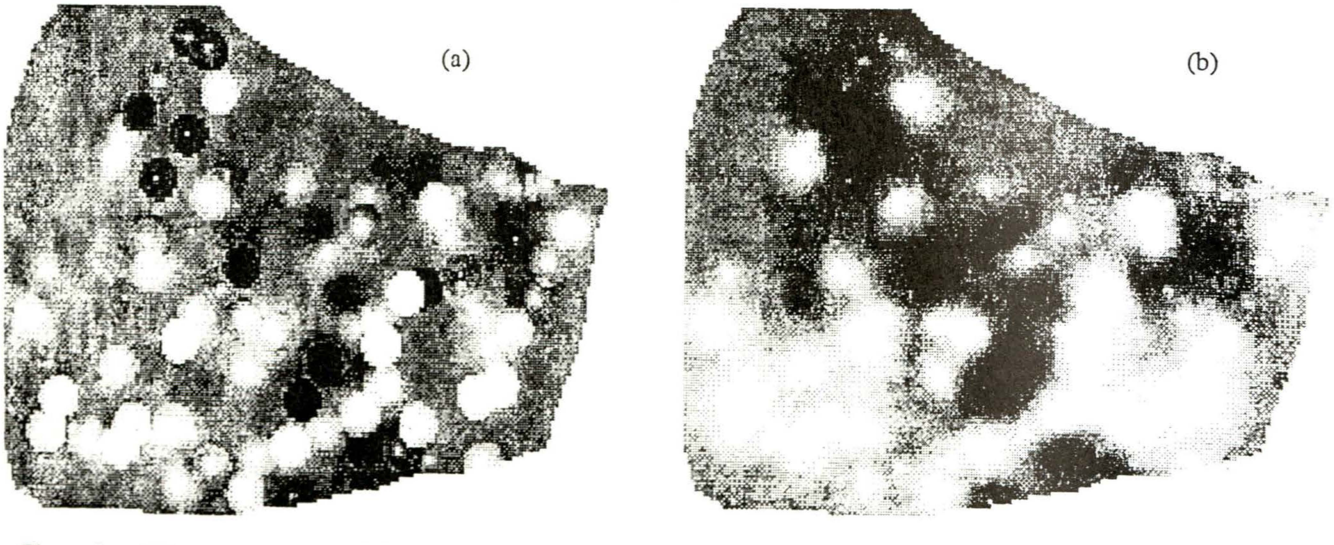


Figure 3.—*"Uncertainty images" for potential old-growth areas on the study watershed from the conditional co-simulation program (a) and from the sequential Gaussian simulation program (b). Darker gray-tones indicate higher probabilities. Note that while striations are absent from figure (a), the definite circles around the sampled points remain.*

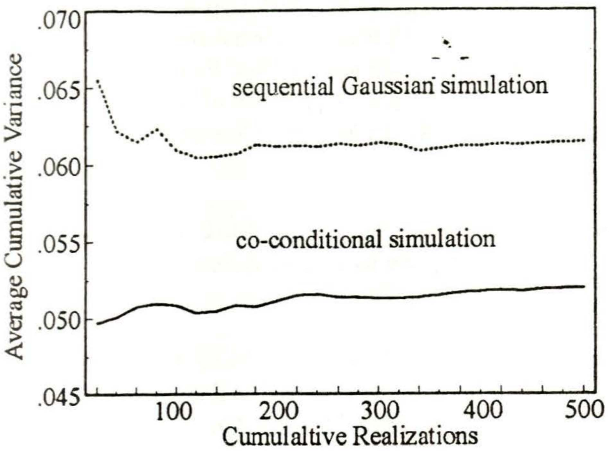


Figure 4.—Average cumulative variance calculated across identical pixel locations and summed over multiple realizations of the co-simulation and the s.G.s. Monte Carlo processes.

s.G.s. realizations. Both have reached an adequately smooth, level value at 500 realizations, indicating stable estimation.

COMPARISON OF RESULTS

To compare the results more closely, "empirical spatial confidence regions" for the two methods are presented in figures 5a (co-simulation) and 5b (s.G.s). These were constructed by selecting cells for the top 90, 95, and 99 percent of the image histogram, and shading them with increasingly darker shades of gray. The delineation of the confidence regions for the co-simulation algorithm is much more geometric than that for s.G.s.. The circles of higher probability surrounding certain measurement points are very pronounced, and similar to the appearance one obtains by simply depicting kriging variances. Visual inspection of an individual turning bands realization (fig. 2a, for example) indicated notable striations, which one would not expect for forestry applications. These have "averaged out" in the cumulative image (fig. 5a).

A puzzling artifact present in the co-simulation image is the inclusion of one or more pixels of low probability in the center of a circle or ring of higher probability pixels. This is difficult to explain in either a geostatistical or ecological context, and appears to be a result of the way the simulation results are combined in the COSIM program, as described above. After careful and protracted scrutiny of the COSIM FORTRAN code, no method was apparent whereby the original data values were retained at their original locations. This is certainly contrary to current descriptions of conditional simulation whereby "resulting realizations honor data values at their locations" (Deutsch and Journel 1998). By contrast, the s.G.s. analysis provides "empirical spatial confidence regions" that are continuous, and understandable from both an ecological and geostatistical perspective.

CONCLUSIONS

While the notable striations, apparent through visual inspection of an individual turning bands realization (fig. 2a) are impossible to justify for forestry applications, they might be desirable for geological applications where linear strata are common. Deutsch and Journel (1998)

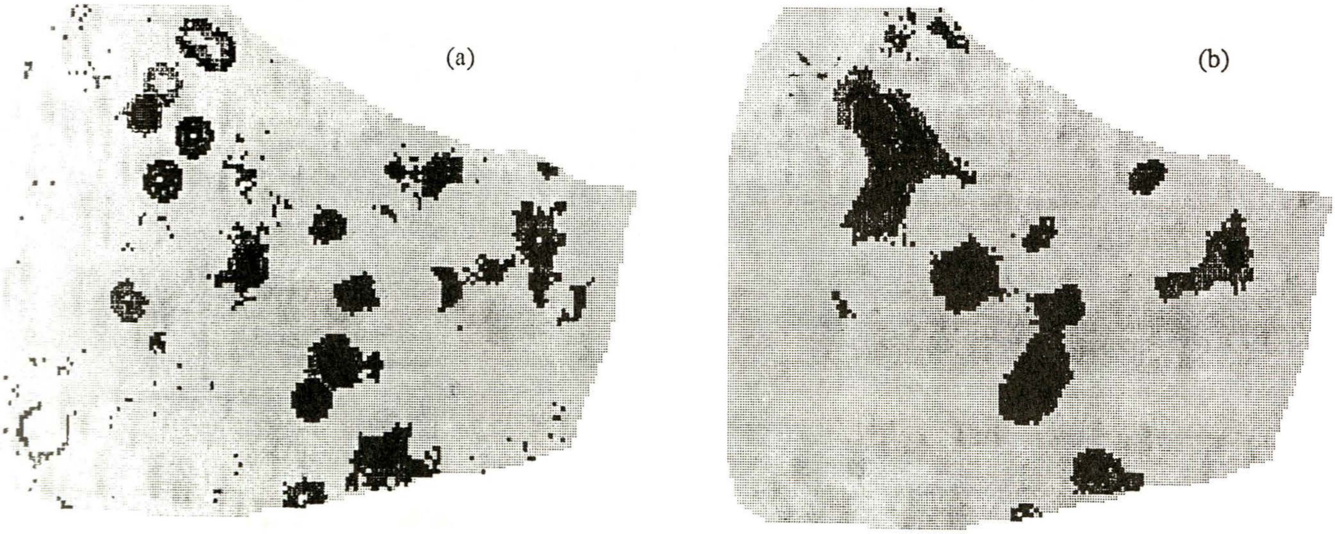


Figure 5.—*Empirical spatial confidence regions for old-growth locations on the study watershed created from the images in figure 3 by selecting the pixels from the image histogram with the top 99 percent (black), 95 percent (dark gray), and 90 percent (medium gray) from the conditional co-simulation program (a) and from the sequential Gaussian simulation program (b).*

note that the striations or "artifact banding" of the turning bands algorithm is due to the coarse partitioning by 15 bands. However, in the current study these striations do not reflect any characteristics of the data. The fact that some of these lines appear consistently lighter or darker than those surrounding them indicates that the turning bands Monte Carlo process does not create completely independent sets of random deviates along these lines. Improving the random number generator and/or increasing the number of lines in the turning bands algorithm would likely minimize these striations. However, in light of the symmetric appearance and seemingly contradictory overall appearance of the empirical confidence regions for the co-simulation technique, efforts to improve the COSIM program would likely not be worthwhile.

The overall symmetrical and circular dispersion of the resulting areas of old-growth is also difficult or impossible to justify ecologically. These seem more the result of the fact that conditioning through cokriging takes place after the randomization process in the co-conditional simulation algorithm. The results from s.G.s. are much more satisfying intuitively and seem much more likely to reflect approximate conditions than are the symmetric circles in the co-simulation analysis. For these data, where all variables are measured at each plot location, the co-simulation algorithm has little to offer. At this point there is no generally available software that provides co-conditional sequential Gaussian simulation. Considering the advantage that cokriging has to offer with regard to improved estimation through extensively measured covariates, such software would be a valuable addition to the geostatistical techniques.

ACKNOWLEDGMENTS

The author wishes to thank the following reviewers for their helpful comments in improving this paper: Ronald E. McRoberts, North Central Research Station, St. Paul, MN, USA, and Gerhard Hunner, Department of Forest Sciences, Colorado State University, Fort Collins, CO, USA.

LITERATURE CITED

Carr, J.R.; Myers, D.E. 1985. COSIM: A FORTRAN IV program for coconditional simulation. Computers and Geosciences. 11(7): 675-705.

Carr, J.R.; Myers, D.E.; Glass, C.E. 1985. Cokriging—a computer program. Computers and Geosciences. 17(5): 111-127.

Czaplewski, R.L.; Reich, R.M. 1993. Expected value and variance of Moran's bivariate spatial autocorrelation statistic for a permutation test. Res. Pap. RM-309. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 13 p.

Deutsch, C.V.; Journel, A.G. 1992. GSLIB: Geostatistical software library and user's guide. New York, NY: Oxford University Press. 340 p.

Deutsch, C.V.; Journel, A.G. 1998. GSLIB: Geostatistical software library and user's guide, 2d ed. New York, NY: Oxford University Press. 369 p.

Goovaerts, P. 1996. Geostatistics for natural resources evaluation. New York, NY: Oxford University Press. 442 p.

Hershey, R.R.; Ramirez, M.R.; Drake, D.A. 1995. Exploring the geostatistical techniques available to create a map of tree species distribution: an example using forest inventory and analysis (FIA) data. In: Analysis in support of ecosystem management, proceedings of a workshop; 1995 April 10-13; Fort Collins, CO. Washington, DC: U.S. Department of Agriculture, Forest Service, Ecosystem Management Analysis Center: 20-30.

Heuvelink, G.B.M. 1998. Error propagation in environmental modeling. London: Taylor and Francis. 127 p.

Isaaks, E.H.; Srivastava, R.M. 1989. An introduction to applied geostatistics. New York: Oxford University Press. 561 p.

Journel, A.; Huijbregts, C.J. 1978. Mining geostatistics. London: Academic Press. 600 p.

Mowrer, H.T. 1994. Spatially quantifying attribute uncertainties in input data for propagation through raster-based GIS. In: Proceedings of GIS 94; 1994 February 21-24; Vancouver, B.C., Canada. Vancouver, B.C. Canada: Polaris Conferences: 371-382.

Mowrer, H.T. 1997. Propagating uncertainty through spatial estimation processes for old-growth subalpine forests using sequential Gaussian simulation in GIS. Ecological Modeling. 98(1997): 73-86.

Pannatier, Y. 1996. VARIOWIN: Software for spatial data analysis in 2D. New York, NY: Springer-Verlag. 91 p.

A Multivariate Decision Tree Analysis of Biophysical Factors in Tropical Forest Fire Occurrence

Rey S. Ofren and Edward Harvey

Abstract.—A multivariate decision tree model was used to quantify the relative importance of complex hierarchical relationships between biophysical variables and the occurrence of tropical forest fires. The study site is the Huai Kha Khaeng wildlife sanctuary, a World Heritage Site in northwestern Thailand where annual fires are common and particularly destructive. Thematic layers of several biophysical variables were combined in a GIS with field measurements of fuel loading and stand physiognomy. Canopy vegetation (NDVI), rainfall, geology, elevation, and forest type explain most of the variation in burned surface across the mountainous landscape. Pixels with normalized vegetation difference index values of 0.7284 best discriminated burned and non-burned areas. Less important decision tree model rules identified fire occurrence thresholds for annual rainfall of 1,285 mm, elevation of 700 m, and distinguished between moist evergreen and dry deciduous formations. A map of the sanctuary was prepared using GIS to illustrate spatial variation in fire hazard probabilities predicted from the decision tree model.

Forest fire is a common event in many human-altered ecosystems in the tropics (Malingreau 1990). However, land managers and policymakers in many tropical countries are not adequately prepared to cope with the increasing forest fire occurrences. Limited resources and financial constraints (Goldammer and Manan 1996) encourage continued development of effective fire management support tools. In forest fire management, there is a recognized need for longer term studies of the relationships between fire regime, landscape heterogeneity, and human land-use (Turner and Romme 1994). Effective management of wildfires requires a thorough understanding of the spatial distribution of vegetation and human land-use, as well as their complex spatial relationships (Chou 1992).

The ecology of forest fires is complex (Underwood and Christensen 1981), but fires tend to be distributed regularly in space and time within fire regimes specific to a vegetation type, topography, and climate (Pyne 1982). Spatial statistical analysis is an effective approach to quantify the environmental interactions and variability of fire at different levels of spatial and ecological organization (Bailey 1994).

The study area is the Huai Kha Khaeng Wildlife Sanctuary (HKK) in northwestern Thailand. This sanctuary is unsurpassed in mainland Southeast Asia in terms of both size and biological quality, leading to its declaration as a World Heritage Site in 1991. It supports extensive stands of rare dry tropical forests and deciduous riparian forest, and a high diversity of wildlife. It also contains a nearly complete representation of the fauna of central Indochina, enriched by some Sundaic and Burmese taxa. Forests at HKK are composed of a mosaic of four different forest types: dry dipterocarp, mixed deciduous, dry evergreen, and hill evergreen. During the wet season, the deciduous forests provide grass and bamboo for grazing wildlife. In the dry season, evergreen forests supply browse and year round shelter.

The average annual rainfall in HKK is approximately 1,500 mm. During the pronounced dry season, two of the four forest types, the dry dipterocarp and the mixed deciduous, are prone to forest fires. Both have a thick understory dominated by grasses and bamboo that can be extremely dry and flammable. However, fire is widely believed to be detrimental to the ecological integrity of the HKK forest mosaic. Seedlings of the evergreen forest are weakened or destroyed when ground fires sweep through the understory because these species have not developed a resistance to fire. Conversely, plant species common in the fire-adapted dry dipterocarp forest are provided with new opportunities for colonization along the edges of the burned evergreen forests (Bunyavejchewin and Baker 1996).

The main objective of this paper is to quantify in a multivariate decision tree model the environmental factors associated with fire occurrence. This statistical model is used to produce a fire hazard probability map of HKK.

SPATIAL MODELING OF FOREST FIRE

The need to simulate the spatial effect of wildfires at landscape scales has resulted in the development of a

---

r.ofren@auckland.ac.nz, Geography Department, University of Auckland, New Zealand, and eharvey@sfu.ca, Simon Fraser University, Burnaby, B.C., Canada.

variety of statistical and analytical models that differ in their complexity and data requirements. These include non-spatial thermodynamic models, and spatially explicit methods from percolation theory, cellular automata, and expert systems. The following specific issues formed the foundation for this paper:

- spatial dimension of fire peculiar to a heterogeneous environment (Campbell *et al.* 1995)
- interaction of variables to identify patterns and processes (Chou 1992),
- probability of occurrence (Vasconselos and Guertin 1992),
- appropriateness of model in tropical regions (Pickford *et al.* 1992), and
- scarcity of local research directed to tropical fire management (Goldammer and Penafiel 1990).

As such, this study incorporates the strength of the integration capabilities of GIS and multivariate statistical modeling to handle spatial data of various forms in analyzing behavior pertinent to the occurrence of fire. Once the susceptibility of the study area to forest fire has been mapped together with a knowledge of its factors' interrelationship, it can be used in forest management as an early warning tool in helping to refine firefighting strategies, direct human land-use, and improve fire prevention and control methods.

MULTIVARIATE DECISION TREE MODEL OF FIRE OCCURRENCE

The statistical methods in this study follow a data-driven (exploratory data analysis) modeling approach in an attempt to identify the variables most strongly associated with fire occurrence. Known locations of previous fire events were used as the baseline information to analyze the biophysical variables associated with fire occurrence and to develop the decision tree model. Multivariate decision tree modeling was adopted because some environmental variables are categorical, others are continuous, and many variables are hierarchically interrelated. These properties are difficult to accommodate in standard linear regression methods.

Decision tree modeling has its origins in artificial intelligence research where the aim was to produce a system that could identify existing patterns and recognize similar patterns in the future (Quinlan 1986 as cited by Moore *et al.* 1991). The hierarchical structure provides an efficient means for sorting observations into classes because at each step, alternative path and/or class assignments are eliminated.

Decision tree models use predictor variables to sequentially split the sample into smaller groups with more pure class membership. The rules are determined by a procedure known as recursive partitioning. This involves splitting the data into subsets based on the first predictor and then identifying entirely different relationships with other predictors in the two resulting subsets. In this manner, the tree model attempts to construct a binary decision tree by selecting the most useful variables from a set of candidate predictor variables (Baker 1993). It provides information about the relative importance and hierarchical interrelationships of variables related to fire occurrence. In this connection, it was adopted to identify environmental variables or groups of variables associated with the occurrence of forest fire.

Data Preparation

Biophysical factors related to the occurrence of fire were drawn from maps of topography, vegetation type, climate, and geology, and field measurements. Maps of the distribution of previous fires were the main source of spatial information of fire occurrence. Field measurements yielded data about fuel type, green weight load, fuel bed depth, and variables related to vegetation physiognomy. Laboratory measurements generated data about fuel moisture content, fuel type proportion, and the estimated fuel bed volume and density. Additional tree canopy data expressed in normalized vegetation difference index (NDVI) were extracted from Landsat Thematic Mapper (TM) data. A Digital Elevation Model (DEM) was used to calculate slope, elevation, and aspect variables. Field sampled fuel and tree physiognomy variables were interpolated over the entire study area. In this respect, topographic gradients and forest cover were used as a basis in interpolating various levels of fuel and tree structures.

The Decision Tree Model

Stratified random sampling was used to select a training sample (Lillesand and Keifer 1987). Spatial variation in forest cover is considered to be the most appropriate variable to stratify the landscape because the type and amount of fuel vary among vegetation formations (Clarke and Olsen 1996). A total of 1,000 randomly selected training pixels were sampled, representing 0.03 percent of the total number of pixels in the study area. Eighty-two percent of the sample was in unburned areas, and 180 training samples were derived from burned sites.

Fourteen biophysical variables were used as predictors to model the binary burned and unburned variable. Slope exposure, forest, and geological variables are categorical variables, while elevation, slope, fuel bed density and load, fuel moisture content, tree density and height, basal area, rainfall distribution, and vegetation index (NDVI) are continuous variables.

The *tree* function in *S-PLUS v3.4* software (Statistical Science 1993) was used to create a decision tree model for classifying fire occurrence as a binary categorical event with an associated probability value:

$$tree(response \sim predictor_1 + predictor_2 + \ldots + predictor_n)$$

Decision tree models capture interactions between variables without explicit specification. This *tree* function also automatically distinguishes between regression and classification trees according to whether the response variable is continuous or categorical, respectively.

Burned and unburned pixels were classified according to the level of the predicted probability. The full tree model yielded 52 terminal nodes representing 52 classification rules. The tree revealed a residual mean deviance (RMD) of 0.2278, equivalent to the discrepancy between the observed and model fitted values. The misclassification error of the model was calculated as 0.053 (94 out of 1,000 observed values did not fall into the terminal leaves). This is an estimate of the predictive skill of the model. The least important predictors (tree canopy closure, average tree height, and basal area) were excluded in the final tree model.

The first, most important rule in the hierarchical model of fire occurrence is the vegetation index (NDVI), then rainfall (second level left split), and then elevation (second level right split) (fig. 1). Pixels in the rainfall subset were further subdivided according to forest (fourth level left split) and geological types (fourth level right split). The latter branch produced the largest number of decision rules.

The position of a predictor variable at the major branches of the tree suggests its dominance in explaining fire occurrence, compared with another variables. The predictor variable with the highest deviance determines the splitting of the data set. Likewise, comparing the deviance of the dominant predictor at a major split with the root node deviance is a simple estimate of the proportion of information explained at each branch of the model. Two parameters—*residual mean deviance (RMD)* and *misclassification error (MCE)*—were also used to quantify the level of improvement when each variable was incorporated into the model generation (fig. 2). In a stepwise manner, a tree model with a particular predictor variable omitted was compared with a tree model based on all variables.

Assessment of Predictors and Attributes

Model Improvement

The overall effect of a predictor variable on the tree model performance is particularly evident in the terminal nodes. A significant difference in *residual mean deviance* and *misclassification error* parameters signifies a variable important for the structure of the full tree model of fire occurrence.

The inclusion of the annual precipitation variable in the full tree model has the most influence on the model structure. Including this rainfall variable reduces the average deviance of the residual by almost 40 percent and increases the predictive ability of the model by 17 percent. This corroborates observations by Malingreau (1990), who asserts that annual rainfall is the most important factor in fire occurrence and frequency in the tropics, due to variations in fuel moisture and loading. Annual precipitation determines the succession of wetness and dryness periods, green biomass accumulation and fuel loading, and soil microorganism activity and litter decomposition.

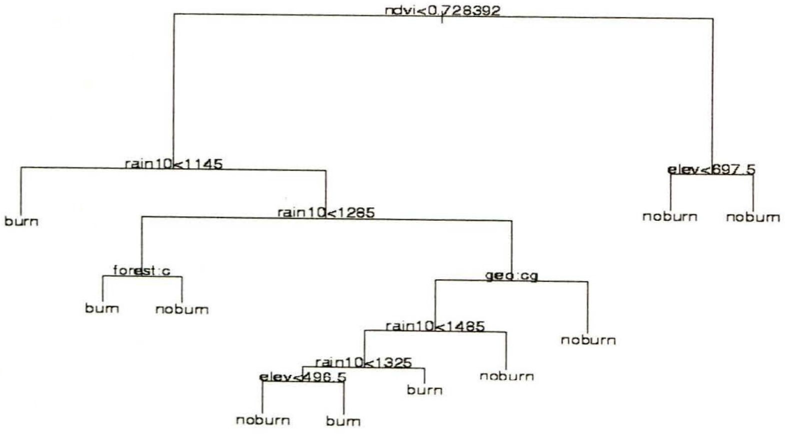


Figure 1.—*Classification tree for fire occurrence (pruned at 10 terminal nodes).*

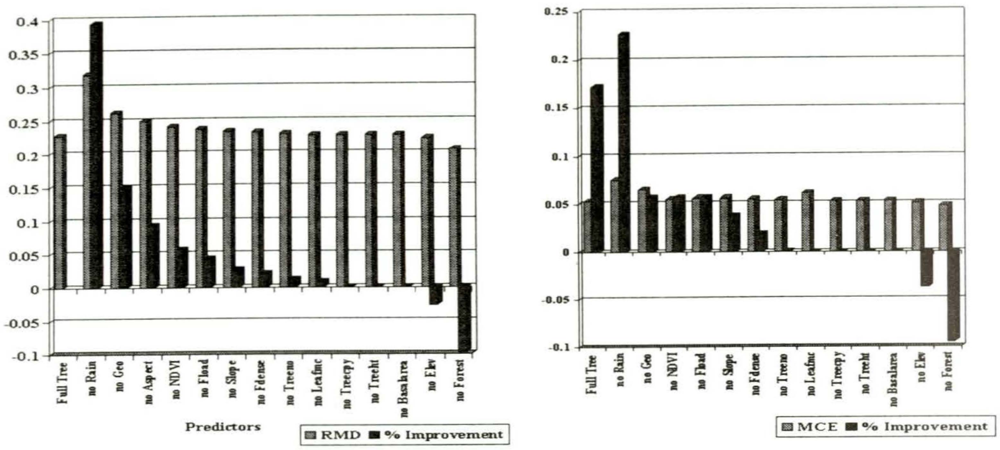


Figure 2.—*Predictors' improvement based on residual mean deviance and misclassification error.*

Geological substrate is the second most important variable in the fire hazard tree model. Parent material influences vegetation indirectly by determining soil nutrient composition (Moore *et al.* 1991). The occurrence of fire among deciduous forests is associated with decreasing soil nutrients and decreasing soil moisture. In the Huia Kha Khaeng wildlife sanctuary, there is a strong association (Pr(2) < 0.0001) between the distribution of forest type and geology. Including the geology variable decreases the average deviance of the residuals by 15 percent and increases prediction by 23 percent.

Aspect has more fire discriminating ability in the decision tree model than the slope variable. Cheney (1981) stressed that changes in fire behavior, even with increasing elevation, are largely associated with changes in exposure. In particular, slope facing the predominant wind direction and solar heating have a considerable effect on fuel moisture content.

The amount of dead fuel load available for burning is the most important fuel-related variable in the decision tree model, other than fuel bed density and dry leaf moisture content. Previous ANOVA statistical analyses revealed that fuel loading is different (Pr(F) = 0.0001) between burned and unburned sites. However, dry leaf moisture content is no different in burned and unburned sites (Pr(F) = 0.619). Stand physiognomy, vegetation index (NDVI), elevation, and slope have a weak correlation with moisture content. Stand physiognomy variables (tree canopy closure, average tree height, and basal area) did not improve the full tree model. They are strongly interrelated and highly correlated with fuel variables, NDVI, and forest type.

Excluding forest type and elevation variables from the model improved the model by 9.7 percent and 2.6 percent, respectively. An examination of the decision tree structure in the next section supports the insignificant contribution of forest type and elevation. In contrast to stand physiognomy variables, both forest type and elevation were retained in the full tree model.

Model Explanation

NDVI did not significantly improve the predictive ability of the decision tree model, but it was an important variable to explain the final model (fig. 3). The appearance of NDVI in the main split of the tree model indicates that burnt and unburnt cases can be best distinguished by a particular vegetation index value (i.e., 0.7284). The relevance of vegetation index in classifying fire occurrence lies in distinguishing evergreen forest against the deciduous type. The distinction between the two major forest types eventually segregates soil parent materials of low (e.g., *gr* – red yellow podzolic soil) or high in nutrient potential and elevation gradient below and above 600 m. Many variables related to NDVI also appear in the deepest branches of the model. Rainfall and elevation variables are the next most important factors in explaining the occurrence of burnt areas. Rainfall accounts for 67 percent of the amount of information in the model compared with 16 percent for elevation.

The rainfall-dominated branch separates into forest and geology subdivisions at 1,285 mm rain per annum. In an area lying in rainshadow where annual precipitation is less than 1,285 mm, the occurrence of fire is primarily dictated by forest type, particularly of deciduous formation. However, the occurrence of fire in the wetter region of the sanctuary (i.e., south to southwest) is no longer governed by forest type but by the complex interactions between geological material, topographic gradients, and fuel variables. The data subset determined by geology

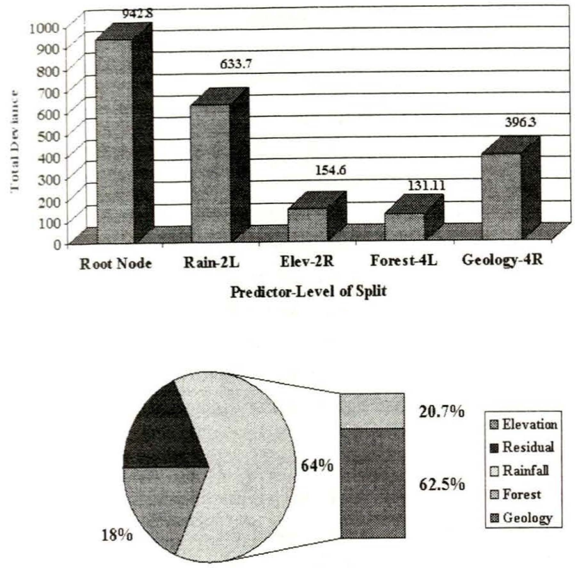


Figure 3.—*Amount and proportion of deviance explained by major predictors in the decision tree model.*

explained 42 percent (62.5 percent of the rainfall subset contribution) of the deviance for the whole model. On the other third branching level, forest type explained 14 percent (20.7 percent of the rainfall subset contribution) of the total deviance. The geology-dominated split exhibits deeper subbranches that accommodate a large combination of rules. Therefore, the main predictor variables can be ordered according to the proportion of total model deviance they explain: vegetation index (NDVI), rainfall, geology, elevation, and forest type.

Several attributes of forest type and elevation appear in distant branches of the model. In contrast to geology, the relatively small contribution of elevation and forest type is attributed to fire distribution, mostly in the moist evergreen forest formation. At higher elevations where moist evergreen forests are abundant, training samples did not provide a distinctive representation of burned and unburnt sites. They dominate unburned pixels at higher altitudes.

SPATIAL IMPLEMENTION OF FIRE HAZARD MODEL

An important use of a decision tree-based model is to predict the value of the response variable for a known set of predictor variables. In this case, an interface between the statistical decision tree model and GIS extends the decision tree into a fire hazard probability map. Decision tree rules were converted into Arc Macro Language (AML) code to map the predicted fire probability for each pixel. The function *docell* in the GRID module of *ARC/INFO* works on a cell-by-cell basis, interpreting the hierarchical rules as a sequence of spatial operations (ESRI 1997). The specific number assigned by the decision tree model to a given tree node represented the navigation process in the tree. Thematic layers of each predictor variable were combined, and a map of predicted probability of fire occurrence was created (see figure 4).

Table 1.—*Discriminatory power of predictors at first major split in decision tree model*

Predictor	**Maximum deviance**	**Attribute**
NDVI	154.40	0.7284
Elevation	142.56	593 meters
Forest	105.64	evergreen/dry dipterocarp, mixed deciduous with and without bamboo
Rain	80.26	1,145 millimeter
Canopy closure (Treecpy)	76.60	70.0%
Geology	76.41	O,Q1,gr/C,E,P,SD,pE
Fuel load (Fload)	72.32	8.32 ton/hectare
Tree height (Treeht)	63.33	33.5 meter
Basal area	59.19	48.19 m^2
Fuel bed density (Fdense)	58.22	0.069 g/m^3
Dry leaf moisture content (Leafmc)	57.16	12.76 %
Tree density (Treeno)	52.49	27 trees/hectare
Slope	7.56	10.5 %
Aspect	6.98	east,flat,north,northeast,southeast,southwest/northwest, south,west

Using the known fire location map as reference, the modeled fire occurrence produced an overall mapping accuracy of 90 percent. A fire probability threshold of 0.60 was used to distinguish between burned and unburned locations. This probability level produced a higher percentage of mapping improvement against the possible random occurrence of burned and unburned locations.

SUMMARY AND CONCLUSIONS

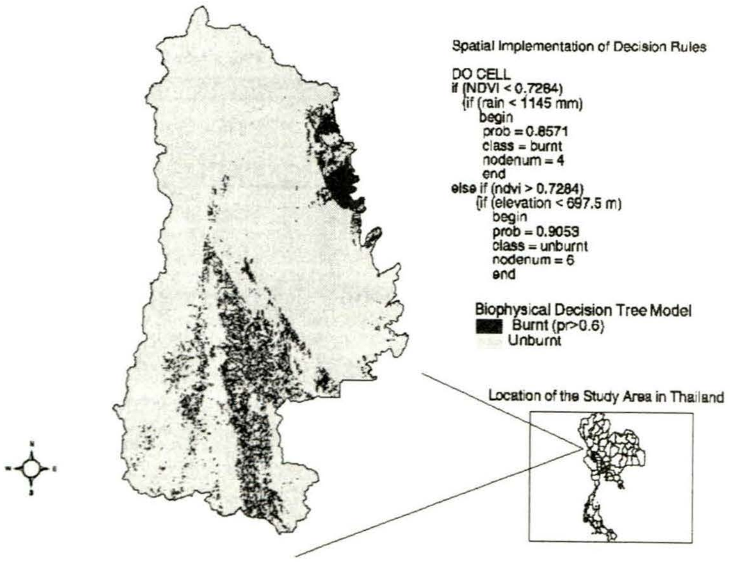
Rainfall, geology, aspect, and NDVI variables significantly improved the predictive ability of the decision tree model. NDVI, rainfall, geology, forest type, and elevation explain most of the processes underlying the hierarchical rules that distinguish between varying probability levels of fire occurrence. NDVI and soil parent materials are highly correlated with forest type, so their importance in the model was apparent.

The overall importance of each environmental variable for improving the predictive ability of the decision tree model was assessed from *residual mean deviance* and *misclassification error* parameters. Vegetation index (NDVI) was ranked fourth after aspect, geology, and rainfall in terms of model improvement, but it appeared to have the highest discriminatory power to distinguish burnt and unburnt pixels.

The insignificant contribution of forest type and elevation in the overall improvement of the predictive ability is attributed to few pixels of burned area in dense vegetation at higher altitudes. At higher altitudes, fire locations are usually confined to a narrow range of slope exposure. These are the manifestations that the decision tree is robust to outliers that tend to be segregated into distinct separate branches. Fire occurring either in dense type of forest or at higher elevations is considered to be an extreme case, but these predictors are not regarded as redundant. Nevertheless, decision tree modeling eliminates the least important redundant predictors (i.e., tree physiognomy) before growing the tree model. Assessing the overall importance of a particular predictor variable for predicting fire occurrence ignores the complex interactions among variables.

The dominance of climate over fuel variables suggests that fire in HKK may be driven by an extreme climatic condition (Bessie and Johnson 1995). This explains the low correlation (r = 0.056) between dry leaf moisture content and stand physiognomy. The dryness of the tree canopy, as represented in NDVI values, integrates the many environmental variables leading to fire situations.

Geographic information systems (GIS) contribute primarily by integrating spatial environmental data with a spatial statistical model and mapping the model predictions. This knowledge-based spatial approach developed predictor-response relationships outside the system and applied them to data in the geographic database. Additional research by the senior author goes beyond the evaluation of fire initiation in point basis but incorporates


Spatial Implementation of Decision Rules

```
DO CELL
if (NDVI < 0.7284)
  {if (rain < 1145 mm)
     begin
      prob = 0.8571
      class = burnt
      nodenum = 4
      end
else if (ndvi > 0.7284)
     {if (elevation < 697.5 m)
        begin
        prob = 0.9053
        class = unburnt
        nodenum = 6
        end
```

Biophysical Decision Tree Model
■ Burnt (pr>0.6)
Unburnt
Location of the Study Area in Thailand

Figure 4.—*Spatial implementation of decision rule model as fire occurrence map.*

the role of neighboring fire. The proximity from the main source of ignition (i.e., human activities) was further integrated towards a more comprehensive model of fire occurrence.

ACKNOWLEDGMENTS

The Royal Thai Forestry Department, the National Research Council of Thailand, and staff of Huai Kha Khaeng Wildlife Sanctuary provided various forms of assistance. Funds from the University of Auckland Graduate Research Fund, the New Zealand Overseas Development Authority, and BIOTROP-GCTE: Southeast Asian Impact Center supported this research. The following people reviewed the manuscript: Jochen Albrecht (Geography Department, University of Auckland) and Kam Suan Pheng (GIS Center, International Rice Research Institute).

LITERATURE CITED

Bailey, T.C. 1994. GIS and spatial analysis for ecological modeling. In: Fotheringham, S.; Rogerson, P., eds. Technical issues in GIS. Taylor and Francis Ltd.

Baker. 1993. Classification and regression tree analysis for assessing hazard of pine caused by *Heterobasidion annosum*. Plant Disease. 77(2): 136-139.

Bessie, W.C.; Johnson, E.A. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. Ecology. 76(3): 747-762.

Bunyavejchewin, S.; Baker, P.J. 1996. Forest fire and the Huai Kha Khaneg Wildlife Sanctuary (http://www.si.edu/organiza/centers/stri/forest/inside.html).

Campbell, J.; Weinstein, D.; Finney, M. 1995. Forest fire behavior modeling intergating GIS and BEHAVE. In: Proceedings of the 9th Annual symposium on geographic information systems. Canada: GIS World, Inc.

Cheney, N.P. 1981. Fire behavior. In: gill, A.M.; groves, R.H.; Noble, I.R., eds. Fire and the Australian Biota. Canberra: Australian Academy of Science.

Chou, Y.H. 1992. Spatial autocorrelation and weighting functions in the distribution of wildland fires. International Journal of Wildland Fires. 2(3): 162-176.

Clarke, K.C.; Olsen, G. 1996. Refining a cellular automation model of wildlfire propagation and extinction. In: Goodchild, M.F., *et al.*, eds. GIS and environmental modeling: progress and research issues. Colorado: GIS World Books.

ESRI. 1997. ARC/INFO version 7.1.2. California: Environmental Systems Research Institute, Inc.

Goldammer, J.; Manan, S. 1996. Fire in tropical forests. ITTO Tropical Forest Update. (6)1: March.

Goldammer, J.G.; Penafiel, S.R. 1990. Fire in the pine-grassland biomes of tropical and subtropical Asia. In: Goldhammer, J.G., ed. Fire in the tropical Biota: ecosystem processes and global challenges. Third symposium on fire ecology, Volkswagen Foundation. IV, Series: Ecological Studies; v.84.

Lillesand, T.M.; Kiefer, R.W. 1987. Remote sensing and image interpretation. 2d ed. John Wiley and Sons.

Malingreau, J.P. 1990. The contribution of remote sensing to the global monitoring of fires in tropical and subtropical ecosystems. In: Goldhammer, J.G., ed. Fire in the tropical Biota: ecosystem processes and global challenges. Third symposium on fire ecology, Volkswagen Foundation. IV, Series: Ecological Studies; v.84.

Moore, D.M.; Lees, B.G.; Davey, S.M. 1991. A new method for predicting vegetation distributions using decision tree analysis in a geographic information system. Environmental Management. 15(1): 59-71.

Pickford, S.; Suharti, M.; Wibowo, A. 1992. A note on fuelbeds and fire behavior in Alang-alang (*Imperata cylindrica*). International Journal of Wildland Fire. 2(1): 41-46.

Pyne, S.J. 1982. Fire in America: a cultural history of wildland and rural fire. Princeton, NJ: Princeton University Press.

Statistical Science. 1993. S-Plus guide to statistical and mathematical analysis, Version 3.2. Washington: Mathsoft Inc.

Turner and Romme. 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecology. 9(1): 59-77.

Underwood, R.J.; Christensen, P.E.S. 1981. Forest fire management in western Australia. Forest Department of Western Australia.

Vasconselos, M.J.; Guertin, D.P. 1992. FIREMAP: simulation of fire growth with a geographic information system. International Journal of Wildland Fire. 2(2): 87-96.

The Use of Multiple Imputation in the Southern Annual Forest Inventory System

Gregory A. Reams and Joseph M. McCollum

Abstract.—The Southern Research Station is currently implementing an annual forest survey in 7 of the 13 states that it is responsible for surveying. The Southern Annual Forest Inventory System (SAFIS) sampling design is a systematic sample of five interpenetrating grids, whereby an equal number of plots are measured each year. The area representative and time series nature of the SAFIS plot design offers increased flexibility in analyzing the data for both large- and small-domain means. Users of FIA information are often interested in the estimates of small-domain means, at the multi-county or FIA survey unit level. Restricting analyses to the most recently measured annual panel results in many missing cells in standard inventory tables. Rather than treat the four unmeasured panels as missing, imputed values are used to update plots in all panels. An initial set of rules and solutions for imputing are provided for SAFIS.

The Forest Inventory and Analysis (FIA) unit of the USDA Forest Service's Southern Research Station is responsible for providing inventory estimates for 13 southern states. Over the last 50 years, the states relied on an approximate 10-year periodic survey, and this system worked well in the past, when resource assessments were less dynamic than today. However, in today's world, the periodic 10-year survey is perceived to be accurate for several years but increasingly unreliable thereafter.

In response to the need for more timely and accurate inventory data, the Southern Annual Forest Inventory System (SAFIS) was initiated in 1997. The SAFIS sampling design is a modification of the periodic design; instead of measuring all plots in 1 to 2 years, an equal number of plots is measured each year, with a plot remeasurement cycle of 5 years. This results in a systematic sample of five interpenetrating grids, and each annual grid is in statistical terms a complete annual panel because the same sample elements (plots) are measured every 5 years (fig. 1).

The expansion factor for each SAFIS plot is 5,760 acres over the 5-year period, and 28,800 acres on an annual basis. This creates some interesting alternatives when analyzing the data, especially when estimates of small domains are desired. There are many examples of subregional analysis of FIA data, and the Southern Station has often suggested to users a minimum area rule of thumb of 1 million acres. Over the full plot cycle of 5 years, this results in an approximate sample size of 173 plots or about 35 plots per year per million acres. If the intent is to estimate inventory on an annual basis, some thought should be given to increasing the information available beyond that of plots measured in the current year. Imputation can provide a cost-effective solution for increasing the information available for any given year.

Imputation is a technique that replaces each missing or deficient value with more acceptable values representing a distribution of possibilities (Rubin 1987). For this study, plot measurements in the four unmeasured panels are considered missing. Imputation methods are seemingly new to forest inventory, because there are few publications that formally address the topic. However, upon further inspection, it is clear that the profession has practiced imputation for several decades, most notably in Scandinavia (Poso 1978, Holm *et al.* 1979). In the United States, many inventory systems have used imputation, although under the label of modeling rather than imputation. The data that are modeled or imputed are treated as actual, and the business of producing inventory estimates proceeds.

Historically, inventories employing imputation have used different methods. For example, the Southern Research Station has at times used a plot matching procedure (Cost, personal communication). The need for imputation has typically resulted from access problems in remote and roadless areas in coastal swamps and wetlands. In this situation, the inventory has relied on a matching donor plot routine that is conceptually similar to the Census Bureau's hot-deck procedure (Sande 1983), while the North Central Station has modeled (projected) plots using STEMS (Belcher *et al.* 1982), an individual tree projection model. The modeled plots are used along with measured plots to produce inventory estimates (Leatherberry *et al.* 1995). The use of models within STEMS to update or "project" plots is an example of

---

Head of Inventory Techniques and Remote Sensing and Mathematical Statistician, respectively, Forest Inventory and Analysis, USDA Forest Service, Southern Research Station, Asheville, NC, USA.

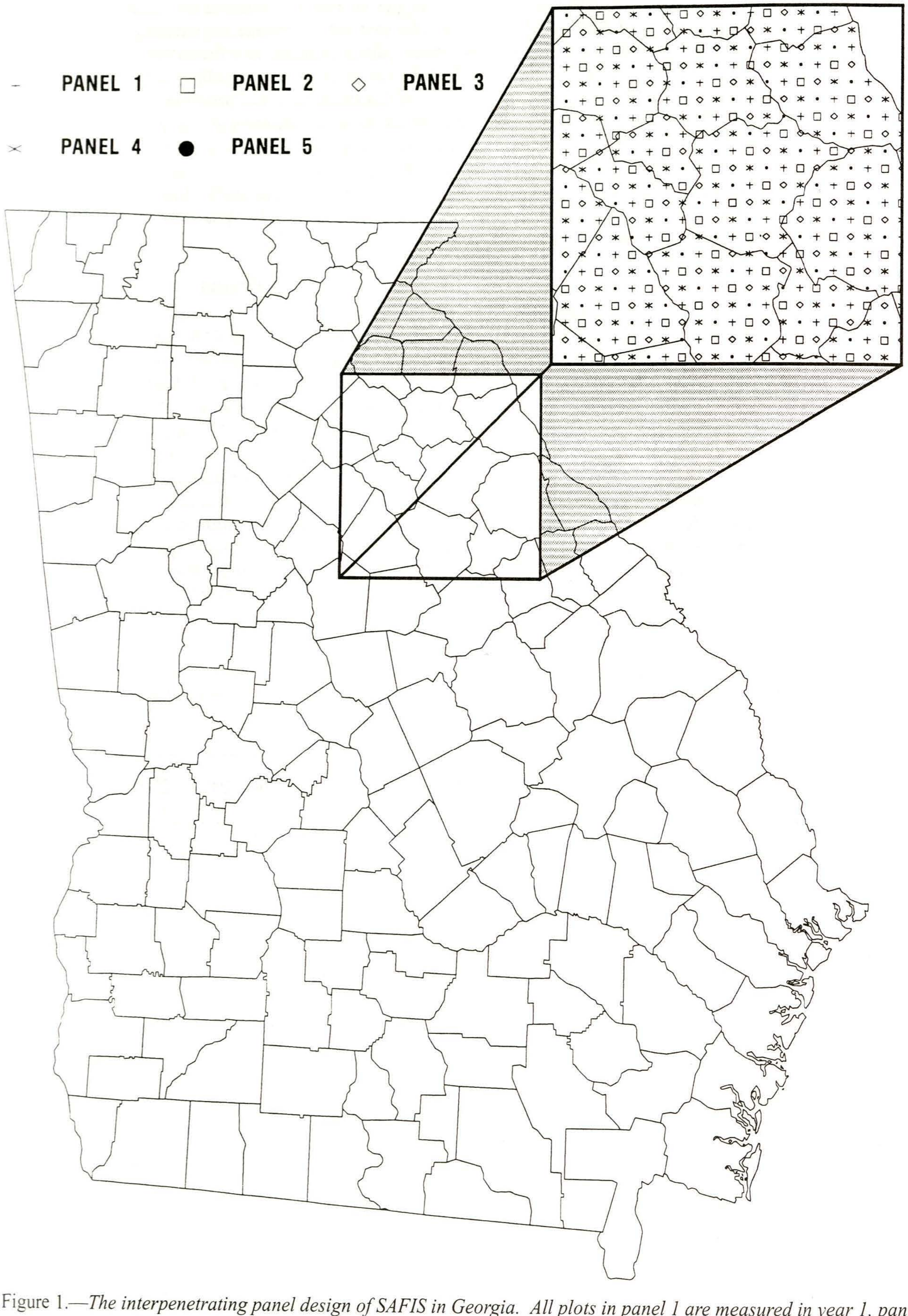

PANEL 1
PANEL 2
PANEL 3
PANEL 4
PANEL 5

Figure 1.—*The interpenetrating panel design of SAFIS in Georgia. All plots in panel 1 are measured in year 1, panel 2 plots in year 2,..., panel 5 plots in year 5.*

mean imputation as defined by Rubin (1987). Obviously imputation works well, because a number of inventories use the concept.

Under SAFIS, if an annual estimate is desired, the simplest solution is to estimate current inventory based on the most recently measured panel. This is an intuitively appealing idea, but there are at least two practical concerns for users. The first concern is that with only one-fifth of the data, there will invariably be missing cells for many of the standard FIA core tables. To illustrate this, a stand table was generated using 20 percent (panel 1 of 5) of the data for survey unit 3 in Georgia (table 1). When compared to the complete set of plots (panels 1 through 5), the panel 1 stand table contains 24 missing cells for softwood species and 37 missing cells for hardwood species. The second concern is that even for commonly occurring forest types, the number of plots measured in a year can be small. Imputation or modeling can increase the available inventory information for any given year.

Given the obvious information gaps that occur when using only current-year data, a reasonable alternative is to retain all the data across the five annual panels and act as if all data are current. In this case, some users will disagree about whether the older panels are deficient.

For example, suppose a destructive hurricane similar to Hugo has occurred. Hurricane Hugo damaged more than 4.5 million acres and reduced softwood volume in affected areas by 21 percent (Sheffield and Thompson 1992). In this situation, use of prior panels is obviously dated given the recent catastrophe. For this and other situations, such as estimation for small domains, an approach where imputation procedures are used to update deficient plot data can prove useful. The following section outlines an imputation procedure for application to small domains.

METHODS

Four adjoining counties in central Georgia (Bibb, Crawford, Monroe, and Jones) were chosen as a small-domain case study. The total area of these counties is slightly less than 1 million acres. The plots in each county were assigned to panels 1 through 5, and sorted by forest type, physiographic class, stand size, stand age, and disturbance history. Except for the most commonly occurring forest types, this resulted in too few observations being available for imputation, and a coarser matching procedure based on forest type and physiographic class was implemented (table 2).

Table 1.—*Number of live trees on commercial forest land, by species and diameter class. Lower case x indicates that trees were observed in panel 1 (20 percent of the full survey), 0 indicates not observed in the full survey, and - indicates observed in full survey but not in panel 1.*

Species	**All classes**	**5.0-6.9**	**7.0-8.9**	**9.0-10.9**	**11.0-12.9**	**13.0-14.9**	**15.0-16.9**	**17.0-18.9**	**19.0-20.9**	**21.0 28.9**	**29.0 and larger**
	- - - - - - - - - *Number of trees* - - - - - - - - -										
SOFTWOOD:											
Longleaf pine	x	x	x	x	x	x	x	x	x	x	0
Slash pine	x	x	x	x	x	x	x	x	-	0	0
Shortleaf pine	x	x	x	x	x	x	x	x	x	x	0
Loblolly pine	x	x	x	x	x	x	x	x	x	x	-
Pond pine	x	-	-	-	-	x	-	0	-	0	0
Virginia pine	-	-	0	0	0	0	0	0	0	0	0
Pitch pine	0	0	0	0	0	0	0	0	0	0	0
Table-Moun pine	0	0	0	0	0	0	0	0	0	0	0
Spruce pine	x	-	x	-	0	0	0	-	-	-	0
Sand pine	x	x	x	-	0	0	0	0	0	0	0
E. white pine	0	0	0	0	0	0	0	0	0	0	0
E. hemlock	0	0	0	0	0	0	0	0	0	0	0
Spruce and fir	0	0	0	0	0	0	0	0	0	0	0
Baldcypress	x	x	x	x	x	x	-	-	-	x	-
Pond cypress	x	x	x	x	-	x	x	x	-	-	0
At. w.-cedar	0	0	0	0	0	0	0	0	0	0	0
E. Redcedar	x	x	x	x	x	x	-	0	0	0	0
Total softwoods	X	X	X	X	X	X	X	X	X	X	-

Table 2.—*Number of FIA plots by panel (P1-P5), forest type, and physiographic class for the counties of Bibb, Crawford, Monroe, and Jones in Central (survey unit 3) Georgia. T represents the total number of plots (P1+P2+P3+P4+P5) by forest type and physiographic class within the four counties. The needed grouping of plots by panel lists the number of current-year plots needed (imputed) to create a current-year data set for all 5 panels. The available number of plots listing is for all plots in survey unit 3 (excluding Bibb, Crawford, Monroe and Jones counties) by panel, type, and physiographic class. All imputed plots come from the available pool.*

Forest	Physio	Observed						Needed					Available				
type	class	P1	P2	P3	P4	P5	T	P1	P2	P3	P4	P5	P1	P2	P3	P4	P5
Longleaf/Slash	Xeric	1	.	.	.	.	1	.	.	.	.	.	2	.	1	1	.
	Mesic	1	.	.	.	.	1	.	.	.	.	.	4	6	6	5	6
Longleaf	Xeric	.	.	.	1	.	1	.	.	.	.	.	1	2	.	.	1
	Mesic	.	.	.	.	.	.	.	.	.	.	.	8	12	10	13	8
Loblolly-Shortleaf	Xeric	.	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.
	Mesic	13	13	10	10	15	61	48	48	51	51	46	88	78	96	69	87
Loblolly	Xeric	1	1	1	.	.	3	.	.	.	.	.	3	3	1	3	2
	Mesic	4	3	5	9	11	32	28	29	27	23	21	63	52	56	58	52
	Hydric	.	.	.	.	.	.	.	.	.	.	.	1	.	.	.	.
Oak-Pine	Xeric	.	.	.	1	.	1	.	.	.	.	.	2	2	1	3	1
	Mesic	6	9	5	5	3	28	22	19	23	23	25	47	48	44	53	38
	Hydric	.	.	.	.	.	.	.	.	.	.	.	.	.	1	.	1
Oak-Hickory	Xeric	.	1	.	.	.	1	.	.	.	.	.	2	4	2	5	3
	Mesic	10	7	11	12	7	47	37	40	36	35	40	102	104	86	97	111
	Hydric	.	.	.	.	.	.	.	.	.	.	.	1	.	2	2	.
Oak-Gum-Cypress	Mesic	2	1	4	.	2	9	.	.	.	9	.	13	19	24	17	18
	Hydric	.	.	.	1	.	1	.	.	.	.	.	21	17	22	29	17
Elm-Ash-Cottonwood	Mesic	.	1	.	1	.	2	.	.	.	.	.	8	8	8	4	2
	Hydric	.	.	.	.	.	.	.	.	.	.	.	3	3	2	.	.

For SAFIS, implementing an imputation scheme is conceptually easy but a bit operationally tedious, especially if all but the current-year's data are imputed. For example, the number of plots by forest type (eight classes), physiographic class (three classes), and panel that must be imputed to replace the four out-year panels with current-year data are listed in table 2 under the needed columns. To further explain, 61 plots across all five annual panels occur on mesic sites and are of loblolly-shortleaf forest type. Replacing the four out-year panels with current-year data for panel 1 requires 48 imputed plots, 48 imputed plots for panel 2, and 46 plots to complete panel 5.

The donor plots for this study are defined as similar plots; the matching is based on same forest type and physiographic class within the same survey unit and annual panel. The numbers of available (donor) plots are listed in table 2. The available pool of plots is composed of all plots in the survey unit except for those in the four counties. The reason for excluding plots within the four counties is that the same sample values would be repeated too often, and the desired goal of imputation is to base the estimates on a full range of plots that more reasonably represent the distribution of possibilities.

When the same sample elements are imputed repeatedly, the situation becomes similar to mean imputation via regression models. Mean imputation is a form of single imputation and results in an underestimate of the variance; the underestimate is directly attributable to the fact that there is no variability in the predicted (imputed) value given the same set of predictants (Ek *et al.* 1997). The underestimate is less pronounced with plot matching procedures because the variability of imputed values is greater since there are multiple donors that meet the match criteria (Rubin 1987). For similar reasons, Sande (1982) recommends adding a random error term to regression-based imputations.

Regression-based imputation as suggested by Sande (1982) is defined as,

$$Y_{imp}=\hat{Y}+\hat{e},$$

where $\hat{Y}$ is the predicted value obtained from the fitted model, which is based on the complete observations, and $\hat{e}$ is the estimated residual that may be obtained by hot deck from the actual residuals of the fitted values or randomly generated using the estimated distribution of the residuals.

For forest inventory, there are at least two advantages of using multiple imputation over single imputation: first, when imputations are randomly drawn in an attempt to represent the distribution of the data, multiple imputation increases the efficiency of estimation. Second, when the multiple imputations represent repeated random draws under a model for nonresponse, valid inferences can be obtained by combining complete-data inferences in a straightforward manner. Because multiple imputation maintains the diversity that is inherent to the data, inventory users and specialists can reach valid inferences using familiar complete-data tools (Van Deusen 1996). The basics of estimation with multiple imputation follow.

MULTIPLE IMPUTATION BY EXAMPLE

Let Q be the quantity of interest in the survey. It could, for example, be $\bar{y}$ or some other parameter that is of interest. For the example presented here, merchantable cubic foot volume per acre of loblolly-shortleaf pine sawtimber stands will be Q. Q is a k-dimensional row vector, and assume inferences for Q based on the assumption that

$$(Q-\hat{Q}) \sim N(O, U)$$

where Q hat is an estimate of Q. After generating *m* simulated-completed data sets and analyzing each of them as if they were genuine complete data sets, we now have *m* estimates for Q and U, i.e., $\hat{Q}_{*1},...,\hat{Q}_{*m}$ and $\hat{U}_{*1},...,\hat{U}_{*m}$.

The *m* repeated complete-data estimates and associated complete-data variances for Q is

$$\bar{Q}_m=\sum_{i=1}^{m} \hat{Q}_{*i}/m \tag{1}$$

which is the mean of means. The total variance of $\bar{Q}_m$ is estimated by

$$T_m=\bar{U}_m+(1+m^{-1})\,B_m \tag{2}$$

where

$$\bar{U}_m=\sum_{i=1}^{m} \hat{U}_{*i}/m$$

is the average of the *m* complete-data variances, and

$$B_m=\sum_{i=1}^{m} (\hat{Q}_{*i}-\bar{Q}_m)(\hat{Q}_{*i}-\bar{Q}_m)/(m-1)$$

is the variance among the *m* complete-data estimates.

The results of a hot-deck imputation (m = 3) for merchantable cubic foot volume per acre of loblolly-shortleaf pine stands on mesic sites in the study area (Bibb, Crawford, Monroe, and Jones counties) are presented in table 3. The columns m = 1, m = 2, and m = 3 list the mean and variance for each of three imputed data sets by panel. Each panel estimate (mean and variance) is composed of 20 percent current-year plot measurements and 80 percent imputed data. The imputed data come from current-year plots within the survey unit (excluding the four counties) that match by forest type (loblolly-shortleaf), physiographic class (mesic), and stand size (sawtimber).

In general, the more refined the matching the more precise the imputations should be. Coarse matching will lead to an increase in both the within- and among-variance components of T_m. The question of how many imputations are necessary has been addressed by case studies and simulation studies. In a simulation study, Rubin and Schenker (1986) found that m = 2 or m = 3 was adequate for non-response rates of up to 60 percent. The application given in table 3 demonstrates that with m = 3 imputations, the imputed mean volumes per acre are quite reasonable and well within the 2 standard errors that one can expect if using only annually measured plots.

The variance estimates for merchantable cubic foot volume by individual imputation and for the multiple (m = 3) imputation indicate what Meng (1994) has demonstrated. That is, multiple imputation confidence intervals will be conservative. Meng (1994) further elaborates that the multiple imputation intervals are narrower than those from corresponding incomplete-data methods.

Using imputation for small domains has several advantages. First, a more complete and accurate set of FIA core tables can be constructed. Second, users and analysts of FIA data can use standard complete-data analysis methods. Third, annual estimates of inventory can be made each year, and this will largely eliminate the need for implicit imputations by external FIA user groups.

Table 3.—*Hot-deck imputations (m=3) of merchantable cubic foot volume per acre (mcfv) for loblolly-shortleaf pine sawtimber stands on mesic sites.* $\bar{Q}_3$ *(Eq. 1) is the mean of means and* T_3 *(Eq. 2) is the total variance of* $\bar{Q}_3$*. Ninety-five percent confidence intervals for mean mcfv from measured plots by panel are listed in the last column.*

	m = 1		m = 2		m = 3		Mean	Total	Measured plots only
	Mean	**Variance**	**Mean**	**Variance**	**Mean**	**Variance**	**of means**	**variance**	**95% CI**
Panel 1	2,145	956,986	1,974	565,976	2,324	796,895	2,147	814,066	2,064 ± 625
Panel 2	2,534	926,783	2,401	1,058,905	2,342	654,787	2,426	893,081	2,378 ± 456
Panel 3	2,191	930,702	2,170	895,794	2,330	916,174	2,230	924,375	2,025 ±1,046
Panel 4	2,359	1,278,874	2,357	1,426,937	2,133	858,295	2,283	1,210,439	2,132 ± 616
Panel 5	2,302	967,298	2,502	1,716,006	2,575	1,560,944	2,460	1,441,316	2,103 ± 663

ACKNOWLEDGMENTS

The following people reviewed this paper: Dr. Francis A. Roesch, USDA Forest Service, Asheville, NC, USA, and Dr. Paul C. Van Deusen, NCASI, Tufts University, Medford, MA, USA.

LITERATURE CITED

Belcher, D.W.; Holdaway, M.R.; Brand, G.J. 1982. A description of STEMS the Stand and Tree Evaluation and Modeling System. Gen. Tech. Rep. NC-79. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 18 p.

Ek, A.R.; Robinson, A.P.; Radtke, P.J.; Walters, D.K. 1997. Development and testing of regeneration imputation models for forests in Minnesota. Forest Ecology and Management. 94: 129-140.

Holm, S.; Hagglund, B.; Martensson, A. 1979. A method for generalization of sample tree data from the Swedish National Survey. Report No. 25. Umea, Sweden: Swedish University of Agricultural Sciences, Department of Forest Survey.

Leatherberry, E.C.; Spencer, J.S., Jr.; Schmidt, T.L.; Carroll, M.R. 1995. An analysis of Minnesota's fifth forest resources inventory, 1990. Resour. Bull. NC-165. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 102 p.

Meng, X. 1994. Multiple-imputation inferences with uncongenial sources of input. Statistical Science. 4: 538-573.

Poso, S. 1978. National forest inventory in northern Finland. In: National Forest Inventory, Proceedings of IUFRO Subject Group S4.02 Meeting, Bucharest, Romania.

Rubin, D.B.; Schenker, N. 1986. Multiple imputation for interval estimation from simple random samples with ignorable nonresponse. Journal of the American Statistical Association. 81: 366-374.

Rubin, D.B. 1987. Multiple imputation for nonresponse in surveys. New York, NY: Wiley. 258 p.

Sande, I.G. 1982. Imputations in surveys: coping with reality. The American Statistician. 36(3): 145-152.

Sande, I.G. 1983. Hot-deck imputation procedures. In: Madow, W.G.; Olkin, I., eds. Incomplete data in sample surveys, Volume 3, Proceedings of the Symposium. New York: Academic Press: 334-350.

Sheffield, R.M.; Thompson, M.T. 1992. Hurricane Hugo effects on South Carolina's forest resource. Res. Pap. SE-284. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 51 p.

Van Deusen, P.C. 1996. Annual forest inventory statistical concepts with emphasis on multiple imputation. Canadian Journal of Forest Research. 27: 379-384.

Estimating Two-Way Tables Based on Forest Surveys

Charles T. Scott

Abstract.—Forest survey analysts usually are interested in tables of values rather than single point estimates. A common error is to include only plots on which nonzero values of the attribute were observed when computing the variance of a mean. Similarly, analysts often exclude nonforest plots from the analysis. The development of the correct estimates of forest area, attribute totals, and their means over the area of interest is described. Program TabGen was written to perform these calculations correctly assuming simple random sampling, stratified random sampling, or double sampling for stratification.

The results of forest surveys generally are produced in the form of one- and two-way tables. For example, forest managers and planners may make decisions based on tables of the area by forest type and stand size or volumes by species and diameter class. The statistical reports of the Forest Inventory and Analysis (FIA) units of the USDA Forest Service are compilations of such tables. Although we regularly use such tables, the forest survey and sampling literature describes sampling designs and alternative estimators for a single attribute of interest rather than for tables of them.

There is confusion over how to construct tables involving a measured variable, e.g., volume, which is then divided into rows and columns by categorical variables, such as stage of development and site class. Typically, the table total is divided into rows that are further broken down into columns. These values are not unrelated estimates because they must add across and down. The literature does not address this issue directly. Sometimes additivity constraints are imposed after estimating each cell independently (Li and Schreuder 1985). For the sampling designs and estimators described here, the tables are constructed to be additive (except for ratio estimators). Because cells are estimated independently, there often is confusion over the sample size of each table cell, which then affects the estimate of precision for that cell.

In many forest surveys, especially in the United States, there is interest in estimating not only various forest characteristics but also forest land area. This requires sampling the entire land area and then estimating the portion that is forested. This creates confusion in sample sizes and in the expression of the values as totals and on a per unit area basis.

In this paper, I present estimators for construction tables of values and their variances. The estimation steps presented are designed to avoid some of the confusion and mistakes described previously. These procedures have been incorporated into a software package called TabGen.

METHODS

The first step in clarifying the estimation of tables is to present the estimators in the context of estimating tables. This is done at some length in this section to set the stage for addressing sources of confusion such as sample size, estimation of forest area, and expressing values on a per unit area basis.

Estimation

Typically, estimators are derived for a single attribute of interest, such as, total biomass of a forest. When estimating tables, one may be interested in estimating biomass by species group and diameter class. The estimation process is the same for each cell—only the attribute of interest changes. Alternatively, the estimation process and the attribute of interest are the same in each cell, but different conditions are placed on the attribute of interest in each table cell. The latter approach is taken here.

Each row and column category can be thought of as a condition to be placed on the attribute of interest. Row and column variables must be categorical or must be continuous variables that have been divided into classes, e.g., diameter classes. The attribute of interest is "summed" into a cell only when it meets the row and column conditions. Each categorical variable has an associated indicator variable—either the attribute is in the category of interest (1) or it is not (0). For example, when estimating the volume in Site Class 3, if the Site Class for the sampling unit (plot or cluster of plots) is 3, the indicator variable for the sampling unit is assigned as 1, otherwise it is 0. So for each cell, indicator variables can be assigned to an observation for each categorical variable (row and column variables)—either the observation

---

Project Leader, USDA Forest Service, Northeastern Research Station, 359 Main RD, Delaware, OH, USA.

belongs in that cell or it does not. This method is described in Cochran (1977, p. 142-144) for estimating domain (cell) means.

These indicator variables can then be used in the estimation process. Because values of 0 and 1 were chosen, the indicator variables can be multiplied times the attribute of interest for each observation. If either the row or column indicator is 0, the product of the two indicator variables and the attribute of interest is zero. This product is then averaged across all sampling units within each stratum. In the simple random sampling case, this is the final estimate because simple random sampling can be thought of as stratified random sampling with a single stratum. However, stratification often is used to reduce the variance of the estimates by subdividing the population into relatively homogenous strata. In this case, the strata means are averaged using the stratum areas as weights (stratified random sampling estimator) or using estimated stratum weights (double sampling for stratification). The variances also are computed using the product of the attribute of interest and the indicator variables.

The formulas that follow assume stratified random sampling where strata are defined on maps or satellite imagery. Examples include map-based forest type, stand-density classes, and land-use classes. The simple random sampling formulas are the same except that there is only one stratum. Double sampling for stratification (Cochran 1977) estimators are the same except that additional terms are added to the variance because stratum areas also must be estimated (see also Chojnacky 1998). Examples include photointerpreted land-cover classes, or volume classes.

The population mean (per unit area) for the attribute of interest in row, r, and column, c, is estimated as:

$$\bar{Y}_{rc} = \sum_{h=1}^{H} \frac{N_h}{N} \bar{Y}_{hrc} = \sum_{h=1}^{H} \frac{N_h}{N\, n_h} \left(\sum_{i=1}^{n_h} Y_{hi} I_{hir} I_{hic} \right) \qquad (1)$$

where:

N_h = area in stratum h, where h=1, 2, ..., H

N = total area in population (across all H strata)

n_h = number of sampling units observed in stratum h

Y_{hi} = attribute of interest (expressed on a per unit area basis) on sampling unit i in stratum h. For example, the sum of tree observations divided by their plot area.

I_{hir} = indicator variable for row r of the first categorical attribute of interest for sampling unit i in stratum h. Equals 1 if the value of the attribute matches row r, but is 0 otherwise.

I_{hic} = indicator variable for column c of the second categorical attribute of interest for sampling unit i in stratum h. Equals 1 if the value of the attribute matches column c, but is 0 otherwise.

In other words, the products of the attribute of interest, Y_{hi}, and the two indicator variables are summed over all sampling units in a stratum and divided by n_h to form the strata means. These means are combined using the stratum weights to form an estimate of the population mean for each cell (r, c) in turn. Whatever the value of Y_{hi}, the contribution of a sampling unit is 0 if either of the indicator variables I_{hir} or I_{hic} is zero.

To estimate the proportion of the area in each table cell (combination of r and c), drop out the attribute of interest from equation (1):

$$\bar{A}_{rc} = \sum_{h=1}^{H} \frac{N_h}{N} \bar{A}_{hrc} = \sum_{h=1}^{H} \frac{N_h}{N\, n_h} \left(\sum_{i=1}^{n_h} I_{hir} I_{hic} \right) \qquad (2)$$

Note that the sum in parentheses gives the number of sampling units that fall in row r and column c within stratum h.

The estimated variances are computed from Cochran (1977, eq. 5.12) as:

$$v(\bar{Y}_{rc}) = \sum_{h}^{H} \frac{N_h}{N} \frac{N_h - n_h}{N_h} v\left(\bar{Y}_{hrc}\right) = \sum_{h}^{H} \frac{N_h}{N} \frac{N_h - n_h}{N_h} \frac{\left(\sum_{i=1}^{n_h} Y_{hirc}^2 \right) - n_h \bar{Y}_{hrc}^2}{n_h (n_h - 1)} \qquad (3)$$

and,

$$v(\bar{A}_{rc}) = \sum_{h}^{H} \frac{N_h}{N} \frac{N_h - n_h}{N_h} v\left(\bar{A}_{hrc}\right) = \sum_{h}^{H} \frac{N_h}{N} \frac{N_h - n_h}{N_h} \frac{\left(\sum_{i=1}^{n_h} A_{hirc}^2 \right) - n_h \bar{A}_{hrc}^2}{n_h (n_h - 1)} \qquad (4)$$

where:

Y_{hirc} = product of attribute of interest and the indicator variables
$= Y_{hi} I_{hir} I_{hic}$

A_{hirc} = product of the indicator variables
$= I_{hir} I_{hic}$

To estimate population totals such as total volume or area of Site Class 3, multiply equations (1) and (2) by the known total area in the population, A_T. Their estimated variances are then equations (3) and (4) multiplied by A_T^2.

If simple random sampling is used, then H = 1 and $N_h = N$. If double sampling for stratification is used, Cochran (1977, eq. 12.32) replaces equations (3) and (4). Note that equations (5) and (6) simplify to (3) and (4) if the total number of first-phase samples (usually interpreted on aerial photographs), N, equals the total area, A_T.

$$v(\bar{Y}_{rc}) = \left(1-\frac{1}{A_T}\right)\sum_{h=1}^{H}\left(\frac{N_h-1}{N-1}-\frac{n_h-1}{A_T-1}\right)\frac{N_h}{N}\,\frac{\left(\sum_{i=1}^{n_h}Y_{hirc}^2\right)-n_h\bar{Y}_{hrc}^2}{n_h(n_h-1)} \tag{5}$$

$$+\left(1-\frac{N}{A_T}\right)\sum_{h=1}^{H}\frac{N_h}{N}\,\frac{\left(\bar{Y}_{hrc}-\bar{Y}_{rc}\right)^2}{N-1}$$

and,

$$v(\bar{A}_{rc}) = \left(1-\frac{1}{A_T}\right)\sum_{h=1}^{H}\left(\frac{N_h-1}{N-1}-\frac{n_h-1}{A_T-1}\right)\frac{N_h}{N}\,\frac{\left(\sum_{i=1}^{n_h}A_{hirc}^2\right)-n_h\bar{A}_{hrc}^2}{n_h(n_h-1)} \tag{6}$$

$$+\left(1-\frac{N}{A_T}\right)\sum_{h=1}^{H}\frac{N_h}{N}\,\frac{\left(\bar{A}_{hrc}-\bar{A}_{rc}\right)^2}{N-1}$$

where:

N_h = number of first-phase samples that fell in stratum h

N = total number of first-phase samples taken to determine strata areas

These equations are all that is needed to construct tables of means for an attribute of interest and for area proportions, and to create tables of their variances under simple random sampling, stratified random sampling, or double sampling for stratification designs.

Sample Size

Note that for estimates of all cells, the sample sizes, n_h, have remained the same. Often, survey analysts assume that the sample size is the number of sampling units that "fell" into a cell, that is, the number of sampling units for which both indicators were 1. Mathematically, this is the sum of A_{hirc}. This sum is a random variable—it was not known (fixed) in advance of sampling (as was the true sample size, n_h). In fact, when the sum is divided by the sample size, it forms an estimate of the proportion of sampling units falling in the cell of interest, which is a random variate (we can estimate its variance in (4)). Another way to understand this is that all attributes of interest are observed on all sampling units but that often the observation is zero.

Often, interest is in the mean of an attribute of sampling units falling in a cell. Unfortunately, the mean estimated in equation (1) is the mean based on all sampling units. Often, these means are difficult to interpret, such as the average volume per acre that includes both forest and nonforest acres. Thus, estimates using equation (1) generally are transformed by multiplying by the total area, A_T, to yield totals across the population. Further, these totals can be divided by the estimated area in each cell resulting in an estimate of the mean of an attribute for sampling units falling in a cell, as shown in the following section.

Expressing Values on a Per Unit Area Basis

Often, interest is in the mean of observations falling within a particular cell, expressed on a per unit area basis, such as the volume per hectare of pine in pine plantations versus the volume of pine on an "average" hectare across the whole forest, as is given by equation (1). Rather than using only sampling units that fall in the cell of interest, all sampling units are used—first to estimate the total volume of pine in pine plantations and then to estimate the total area of pine plantations. Dividing the total by the area then gives a biased (of order 1/n) estimate of the attribute of interest on a per unit basis for the area of interest. This is equivalent to dividing the mean across the whole forest (1) by the proportion of the area in the class of interest (2):

$$R_{rc} = \frac{\bar{Y}_{rc}}{\bar{A}_{rc}} \tag{7}$$

The approximate variance of this combined ratio-of-means estimator (Cochran 1977, eq. 6.51) is:

$$v(R_{hrc}) = v(\bar{Y}_{hrc}) + R_{rc}^2\, v(\bar{A}_{hrc}) - 2\, R_{rc}\, cov(\bar{Y}_{hrc}, \bar{A}_{hrc}) \tag{8}$$

where:

$$v(R_{hrc}) = v(\bar{Y}_{hrc}) + R_{rc}^2\, v(\bar{A}_{hrc}) - 2\, R_{rc}\, cov(\bar{Y}_{hrc}, \bar{A}_{hrc})$$

$$v(R_{hrc}) = v(\bar{Y}_{hrc}) + R_{rc}^2\, v(\bar{A}_{hrc}) - 2\, R_{rc}\, cov(\bar{Y}_{hrc}, \bar{A}_{hrc})$$

Note that a single estimate of the ratio is used rather than one for each stratum. The covariance between Y_{hrc} and A_{hrc} is estimated as:

$$cov(\bar{Y}_{hrc}, \bar{A}_{hrc}) = \frac{\left(\sum_{i=1}^{n_h} Y_{hirc}\, A_{hirc}\right) - n_h\, \bar{Y}_{hrc}\, \bar{A}_{hrc}}{n_h\,(n_h - 1)} \tag{9}$$

Analogously, an approximation to the estimated variance in the double sampling for stratification case is:

$$\begin{aligned} v(R_{rc}) = {} & \frac{1}{R_{rc}^2}\left(1 - \frac{1}{A_T}\right) \sum_{h=1}^{H} \left(\frac{N_h - 1}{N - 1} - \frac{n_h - 1}{A_T - 1}\right) \frac{N_h}{N}\, v\!\left(R_{hrc}\right) \\ & + \frac{1}{R_{rc}^2}\left(1 - \frac{N}{A_T}\right) \sum_{h=1}^{H} \frac{N_h}{N\,(N-1)} \left(\frac{\bar{Y}_{hrc}}{\bar{A}_{hrc}} - R_{rc}\right)^2 \end{aligned} \tag{10}$$

This process is repeated for each combination of the categorical variables, plus the total across all classes (row and column margins). This provides all of the formulas needed to construct a variety of tables for attributes of interest, area, and the ratios between the two. Note that if estimates are to be placed on a per observation basis, e.g., per tree, A_{hi} values should be replaced with the number of observations per acre.

Estimation of Forest Area

Forest inventories for an ownership typically are map based, and only forest areas are sampled. In regional forest inventories such as FIA, no maps of all forested areas are available, so forest area must be estimated from the sample. The forest area is estimated easily using equation (2). The categories of interest are forest and nonforest. The proportion of sampling units falling in forested conditions times the total land area sampled, A_T, yields an estimate of the total forest area. Because remaining tables would focus only on the forested sampling units, it is tempting for the analyst to use only the forested sampling units in further analyses. However, the number of forested sampling units is a random variable, so all sampling units must be included in all analyses. This is done using the methods described earlier. FIA often presents the results as totals, A_T times equation (1), to simplify the estimation. Means across forest and nonforest areas, as given in equation (1), are rarely useful; means generally would have to be estimated using equation (7) with total forest area or some subset of it as the denominator. This is more complicated because it uses equations (1)-(4) and (7)-(9), rather than only (1)-(2).

Program TabGen

To avoid these complexities and confusion, program TabGen (Table Generator) was developed. Written in Visual Basic, TabGen allows the user to create tables in a point-and-click environment. It uses all the formulas presented here and avoids the pitfalls mentioned.

Currently, the program reads a flat file for each of the following: plot (sampling unit) data, site index trees, regeneration, overstory trees, and fields common to both regeneration and overstory trees. Although other files can be substituted, a hierarchy of one plot file and one or more files with multiple observations per plot is assumed. TabGen also reads a control file that contains the stratum weights, N_h, the total area, A_T, and a list of plots that will be included in the analysis. This list allows the analyst to include only the subset of plots of interest. We have a script in Arc/Info (or ArcView) that creates this file based on the areas that have been selected using the GIS.

When the user selects the control file, TabGen reads a variable library (dictionary) that describes the variables that are read from each file, whether they are continuous or categorical, and, if categorical, the labels for each category. The program also allows the user to create categorical variables from continuous ones by assigning ranges to categories. The user then selects the row and column categorical variables and the attribute of interest (continuous variable). The results can be viewed as:

1. The percent of the area or total area in each cell—equation (2)
2. The mean or total of the attribute of interest in each cell—equation (1)
3. The ratio of the mean to the area estimate for each cell—equation (7)
4. The mean of individual observations (generally on a per tree basis)
5. The number of plots "falling" in each cell

The 95 percent sampling errors (confidence limits) are given for each cell:

$$SE\% = 100\, t\, \frac{\sqrt{V}}{\bar{X}} \approx 200\, \frac{\sqrt{V}}{\bar{X}} \qquad (11)$$

where:

t = Student's t-value with = 0.05 and n-H degrees of freedom. As n-H goes to infinity, t goes to 1.96; thus, 2 is substituted.

V = variance estimate of the mean

The estimates and their variances are computed using simple random sampling, stratified random sampling, or double sampling for stratification estimators.

TabGen generates one- or two-way tables, although filters can be used to create a series of two-way tables to create three-way tables. A filter is a rule created for a variable that determines which plots or observations will be included/excluded from the analysis. Multiple filters can be created for each variable. For example, a tree-size filter can be created from dbh. A table of volume by species and site class can be created first for poletimber trees and then for sawtimber trees. Filters also can be used in combination, for example, adding a filter only for pine plantations.

TabGen was written for a specific study, so it is not yet as general as it might be. However, it is public domain software and is available for modification for other purposes. Copies of TabGen are available from the author (cscott/ne_de@fs.fed.us).

CONCLUSIONS AND RECOMMENDATIONS

The literature provides little guidance on the estimation of tables, so survey analysts often encounter problems when summarizing forest surveys. A common problem results when using sampling units that fall into a particular category of interest to compute means. When simple random sampling is used, the means and perhaps the variances are correct. However, when stratified random sampling, double sampling for stratification, or unequal probability sampling is used, this "shortcut" yields inaccurate means and variances. The methods shown in equations (7)-(9) yield the correct results in all cases.

Survey analysts may wish to ignore nonforest sampling units, but they are part of the sample and must be included in the analysis. TabGen uses the methods described above and gives the survey analyst considerable flexibility to generate a variety of tables from forest survey data. However, the analyst must understand the estimation process to avoid drawing erroneous conclusions.

ACKNOWLEDGMENTS

I gratefully acknowledge the support of Mead Paper Corporation and thank Scott Klopfer for his part in programming TabGen. The following people reviewed this manuscript and contributed markedly to it: Stan Arner, USDA Forest Service, Radnor, PA, USA; Bill Bechtold and Stan Zarnoch, USDA Forest Service, Asheville, NC, USA; and Dave Chojnacky, USDA Forest Service, Ogden, UT, USA.

LITERATURE CITED

Chojnacky, D.C. 1998. Double sampling for stratification: a forest inventory application in the Interior West. Res. Pap. RMRS-RP-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 15 p.

Cochran, W.G. 1977. Sampling techniques. New York: John Wiley & Sons. 428 p.

Li, H.G.; Schreuder, H.T. 1985. Adjusting estimates in large two-way tables in surveys. Forest Science. 31: 366-372.

Spatial Terrain Analysis for Matching Native Tree Species to Sites: A Methodology

Robin N. Thwaites

Abstract.—Predicting the distribution of preferable biophysical sites for three of the favored plantation species—*Araucaria cunninghamii*, *Eucalyptus cloeziana*, and *Flindersia brayleyana*—is necessary for private land rehabilitation in tropical north Queensland. The distribution of these predicted sites is expressed in a spatial and quantitative form. Sites are characterized by soil and terrain qualities, within known climatic parameters, using spatial analytical techniques afforded by the predictive capacity of digital terrain models (DTM's) and conceptual regolith-terrain relationships in an explicit approach.

Knowledge-based relationships and recorded soil-topographic data are used to create conceptual models of climatic, terrain, and parent material interaction. These guide the algorithms for digital terrain analysis through use of pedotransfer functions and topographic DTM derivatives. The spatial arrangement of potentially favorable sites is classified through fuzzy means. This form of classification provides multiple membership values for given regolith-terrain attributes for each raster cell in a GIS.

Degraded and poorly utilized pasture lands in the Atherton Tableland region of north Queensland's "Wet Tropics" are being planted with native rainforest and allied timber species. This is an attempt at maintaining biodiversity and rehabilitating degraded lands under private ownership, as well as providing alternative commercial productivity (CRC-TREM 1998). The federal government introduced the Community Rainforest Reforestation Program (CRRP) to help implement and develop this initiative because of the loss to the forestry and timber industries in and around the World Heritage Area national park declaration (CRRP Annual Report 1992-1993 unpublished).

The CRRP has environmental information of variable quality to work with; one of the most critical types is soil information. Soil surveys of varying ages, scales, and relevance have been undertaken for the developed areas of the southern Tablelands but not for the native forest regions. Therefore, knowledge of physical site preferences for most of the target species being recommended for planting (14 in all) is limited. Geological information is being used as a surrogate for soil data, a practice that is inappropriate for several philosophical and practical reasons (Thwaites 1998). The current belief from interpreting current and previous trials is that rainforest site quality is influenced by mesoclimatic and topographic factors as well as parent material and soil moisture (R. Keenan, Queensland Forestry Research Institute, unpublished data; A. Irvine, CSIRO, unpublished data). This ideology forms the basis of this study.

The intention of this study is to predict the distribution of preferable biophysical sites in the Atherton Tablelands for 3 of the 14 species favored by the CRRP: hoop pine (*Araucaria cunninghamii* Aiton ex D. Don), Gympie messmate (*Eucalyptus cloeziana* F. Muell.), and Queensland maple (*Flindersia brayleyana* F. Muell.). There is little recorded information on the site preferences of these species, and even less on the other 11 favored species. Current indications are that an unsatisfactory proportion of the CRRP plantings are showing poor early growth. The individual site characteristics are not known and, therefore, are not being managed appropriately. More confidence is required in choosing appropriate species for sites and in deciding how to manage them for optimal growth and yield.

This paper outlines a methodology for forest site characterization, which is not only explicit and replicable for the information user, but also makes full use of current knowledge environmental and geoecological processes in a scientific analytical framework.

The process involves the use of digital terrain analysis as it is related to field regolith-terrain[1] analysis. The forest-species sites (here termed "toposites," because of their

---

Lecturer in Land Resource Science, Faculty of Natural Resources, Agriculture and Veterinary Science, The University of Queensland, St Lucia, Queensland, Australia.

[1] *The regolith is the complete unconsolidated material within and beyond the solum (the A and B horizons of soil) and is inherently linked to geomorphological surface form and process of the terrain.*

generation through terrain analysis) are determined in a spatial and quantitative form. This is compatible with modeling the species' site suitability over the area using GIS (geographic information system). These toposites are characterized by regolith (including soil) and terrain qualities using DTM's (digital terrain models) involving soil-landscape relationships in an explicit and objective way (Thwaites 1998). Much of the supporting data to define species preferences has to be synthesized from expert knowledge using notional relationships and integrated with the spatial "hard" data on regolith and terrain. Notional relationships are expressed at the empirical level as two-dimensional cause-and-effect notions about species for which there is little real empirical data available to provide statistical predictions. The relationships are expressed through two-dimensional response curves—of the kind: "more is worse/better," "extremes are worse/better," etc.—that are now commonly used in multi-objective decision support systems (MO-DSS) using personal knowledge (El-Swaify and Yakowitz 1998, Lane *et al.* 1991).

THE STUDY AREA

The targeted region for this study is part of the Atherton Tablelands inland of the high coastal range in the "Wet Tropics" of northern Queensland. The study area encompasses approximately 990 km^2 of upper catchments of the Barron and North Johnstone Rivers adjoining the World Heritage Area rainforests. Hence it is termed the Upper Barron/Upper Johnstone (UB/UJ) Key Area. Summary details of the area are given in table 1. Much of this region, which adjoins and includes some of the rainforest conservation areas, is given over to dairy cattle grazing and some beef cattle grazing. Parts of this grazing land are rugged, with short, steep slopes (ranging up to 80 percent gradient) and susceptible to surface erosion - dependent upon soil type and rainfall characteristics.

SITE PREFERENCES FOR TARGET SPECIES

Site preference information for the three species had to be ascertained without the benefit of long-term, specifically designed trial work. It comes from currently available recorded information and expert knowledge. This then can be associated with the notional relationships of the soil-landscape to these species to provide a provisional land suitability model (fig. 1).

Environmental factors that influence the growth of the target species that can be readily ascertained depend on prior trial work and observations of species presence in the course of botanical survey. An environmental profile for each species was developed using known relationships in plantation trials and derived relationships from deductive environmental modeling (Sneddon 1997). The results of the climatic analysis (discussed below) are then used with soils and other environmental data from prior trials to construct a comprehensive environmental profile for each of the three species through the Plantgro computer model. Plantgro 2.1 (Hackett and Harris 1996) expresses the growth potential for any usable species under defined environmental conditions. It is a decision-support system that provides expert systems for recording personal knowledge and combines experimental data to predict overall plant performance at an empirical level at the appropriate, but relatively coarse, local scale (Hackett 1995a). It can therefore be used at the end of the site prediction process to predict growth potential of species in plantation in any individual site. It is not a spatial model and cannot, therefore, be integrated directly with the GIS framework of this site-prediction methodology, although it can be linked to GIS by replicating the spatial distribution of like sites. Plantgro uses a starter data-set system called "Infer" to generate initial species preference characteristics (Hackett 1995b). Little work has previously been undertaken in producing environmental

Table 1.—*Environmental information for the UB/UJ Key area*

Elevation range: 1,100-1,200 m (3,630-3,960 ft) in south and west to 600 m (1,980 ft) in north. Common relative relief range: 100-200 m (330-660 ft).

Landform pattern: Undulating on old basalt plateau, through rolling low hills in the metasediments and midage lavas, to rolling to very steep hills in the recent basalts.

Climatic zone: Subtropical, strongly summer seasonal rainfall with a strong gradient from 3,500 mm in the southeast mountain zone (Johnstone River gorge) to 1,200 mm in the northwest tablelands zone (the town of Atherton). Eighty-five percent falls between November and April (heavy rain January-March). The "critical rainfall deficit" period is October-November, which if dry (after the winter dry), restricts the distribution of many rainforest and allied species.

Geology: Succession of basalt flows in three provinces: "Old," "Middle-age," and "Recent"; Scoria/volcanic materials from Pleistocene eruptions; Low-grade metasediments; Acid volcanics (dom. Rhyolite) around; and Granites in the southern part.

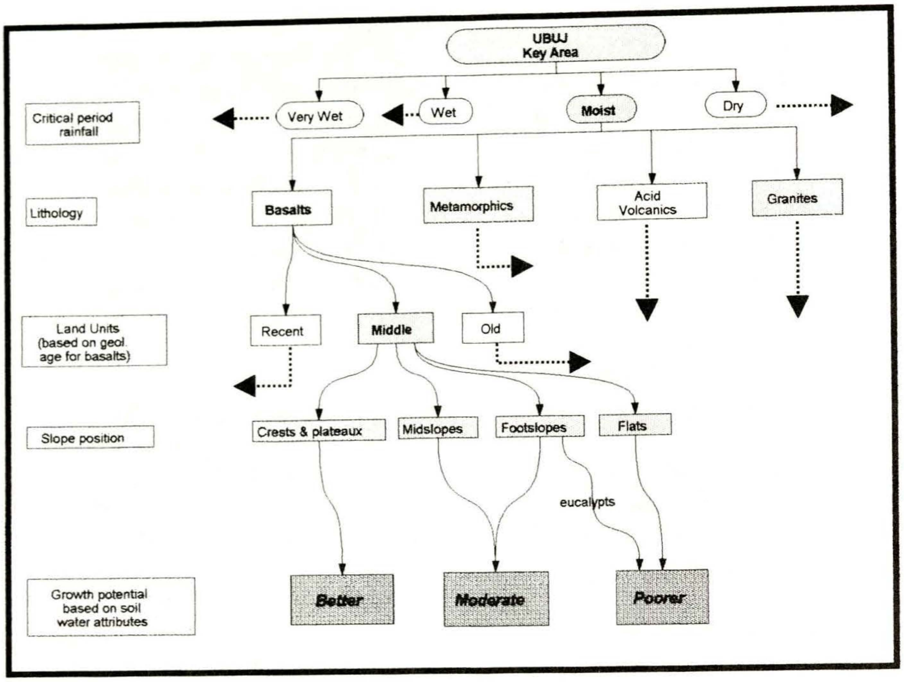


Figure 1.—*Part of the conceptual model used to combine trial information and expert notional relationships to develop rainforest species suitability in N. Queensland which is quantified for running in Plantgro. This example emphasizes the Basalt "geological zones" in the "Moist" climatic zone.*

profiles for native tree species. Plantgro is valuable in this situation because it is a knowledge-based system that helps formalize and quantify expert knowledge in the form of notional relationships.

Climatic Analysis

Using spatial data of species presence only, the natural climatic envelope for each of the target species was ascertained using BIOCLIM, a package within the ANUCLIM 1.2 suite of climatic modeling packages (McMahon *et al.* 1997), and a 10-second resolution digital elevation model (DEM) of Queensland produced by the Queensland Department of Natural Resources (QDNR). BIOCLIM is a two-part package that can calculate bioclimatic values at a set of sites to generate a bioclimatic profile using up to 35 climatic parameters. Not all parameters are possible to use because of restrictions in reliable climatic data recorded. All parameters relate to the following five meteorological variables that strongly influence the distribution of plant species: Max. temperature; Min. temperature; Rainfall; Radiation; and Evaporation. Monthly time steps to create climatic surfaces were selected for the UB/UJ Key Area (Sneddon 1997).

The second part of BIOCLIM is BIOMAP, a stand-alone program that matches the bioclimatic profile generated in BIOCLIM to the bioclimate at any nominated points on a regular grid (McMahon *et al.* 1997). This generates the bioclimatic predictions of spatial distributions of the target species in a bioclimatic context extrapolated from known natural occurrences of the species.

There is a striking meteorological gradient over the Atherton Tablelands associated with the range of relief from 1,600 m elevation at the coastal Bellender Ker mountain range to 600 m elevation at the Barron River near the town of Atherton. Because of this strong gradient, further automatic meteorological stations were recently installed to improve the reliability of climatic modeling through ANUCLIM. New data from these stations will augment the current climate surface modeling in the region, including the UB/UJ Key Area.

REGOLITH-TERRAIN RELATIONSHIPS AND DIGITAL TERRAIN ANALYSIS

The bioclimatic surfaces created through ANUCLIM were used to stratify the UB/UJ Key Area. From this stratification at the broader, regional scale, the most potentially suitable areas for growing the three species were identified, which then became foci for toposite prediction through regolith-terrain and digital terrain analysis at the more detailed landscape scale.

Broad-scale geology maps (1:250,000) of the area have been used by CRRP and QDPI (Queensland Department of Primary Industries) practitioners for gauging soil character, although some previous soil mapping of the region has been undertaken—primarily that of Laffan (1988) at 1:100, 000 scale. Recent soil mapping of the Atherton Tablelands by the QDNR has been completed at 1:50,000 scale (Malcolm 1998). This scale is still too coarse to characterize sites meaningfully for small-scale forest plantation planning. Nonetheless, this soil mapping has aided the development of regolith-terrain models for the UB/UJ Key Area by identifying parent-material provinces and soil-slope relationships. This soil information, augmented by field analysis of regolith exposures and associated terrain characteristics, provides the basis for conceptual regolith-terrain models of the landscapes for the parent-material provinces (fig. 2). These conceptual models guide the algorithms for digital terrain analysis through use of field pedotransfer functions and digital topographic derivatives from simulation of terrain-surface form and process by DTM analysis.

Pedotransfer functions (see Bouma and Van Lanen 1987 for a discussion of the concept) are used as surrogates for soil/regolith parameters that have not been recorded in the process of soil survey, or are impractical to record on any operational scale. An example for soil moisture properties used here is the substitution of soil field texture, structure, organic matter (OM) content, and horizon (or soil layer) depth in a known functional relationship for the measurement of soil bulk density. More complex parameters such as hydraulic conductivity or soil moisture retention can likewise be substituted with more easily, and regularly, measured soil properties in known functional relationships.

The digital topographic derivatives used here include slope curvature in plan, profile and tangential form, aspect and shade, as well as that of the topographic wetness index (TWI), a specific-area contribution formula using a flow-routing algorithm (see Moore *et al.* 1993).

Wetness Index = $\ln(A_s / \tan\beta)$

Where A_s is the specific catchment area (the upslope area draining to any point), and β is the slope angle.

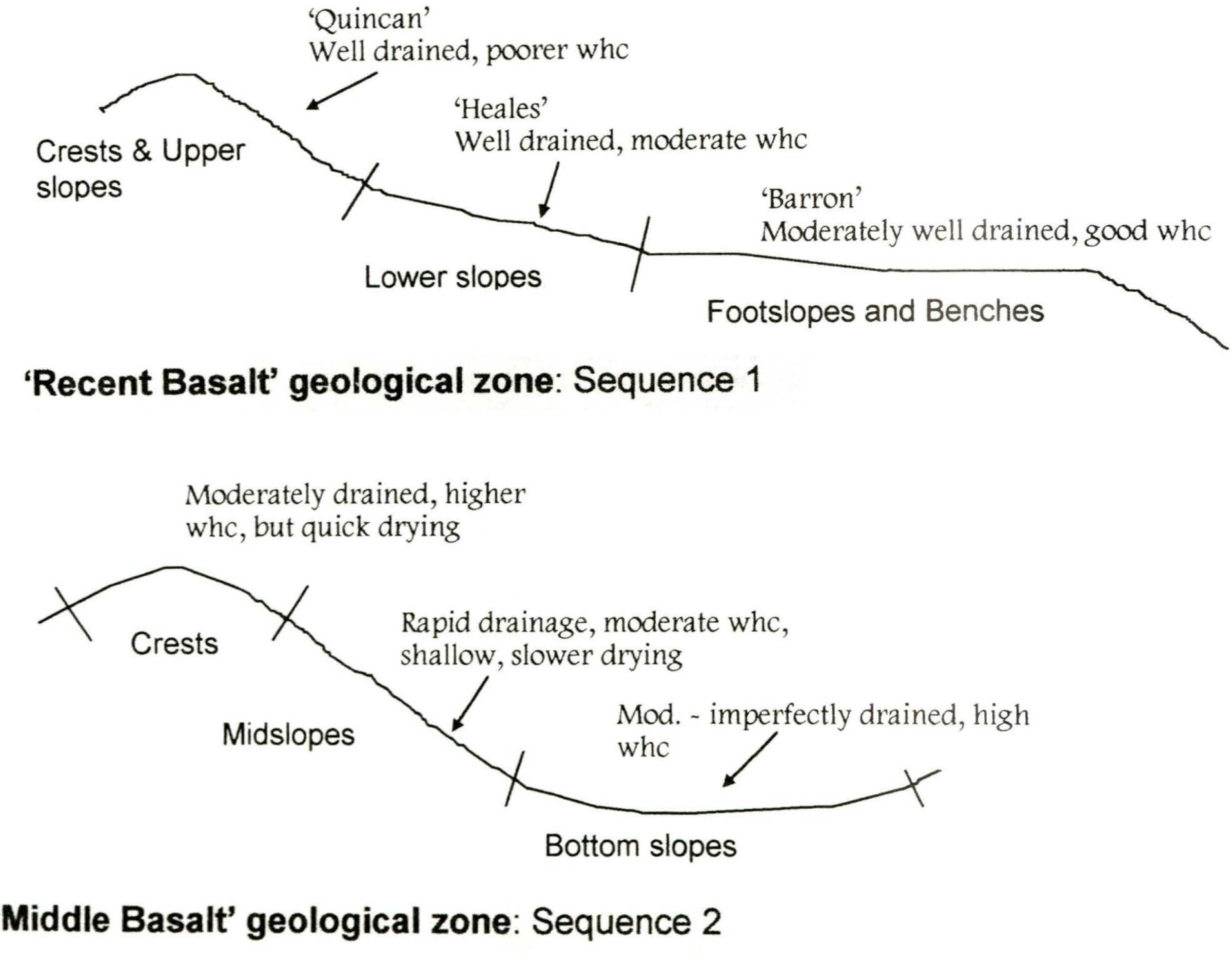

'Quincan'
Well drained, poorer whc
'Heales'
Well drained, moderate whc
Crests & Upper slopes
'Barron'
Moderately well drained, good whc
Lower slopes
Footslopes and Benches
'Recent Basalt' geological zone: Sequence 1
Moderately drained, higher whc, but quick drying
Crests
Rapid drainage, moderate whc, shallow, slower drying
Midslopes
Mod. - imperfectly drained, high whc
Bottom slopes
'Middle Basalt' geological zone: Sequence 2

Figure 2.—*An example of the conceptual model of topographic, soil, and parent material relationships for part of two of the Basalt geological zones in the UB/UJ area. (whc: water holding capacity).*

These topographic attributes were derived using TAPES-G (CRES 1996), a grid-based program for digital terrain analysis. The resolution of the DEM created for the UB/UJ Key Area is 30 m (cell size). It was extensively corrected hydrologically to eliminate artifacts of mathematical interpolation. This model proved satisfactorily accurate in tests to reconstruct the contours and streamlines data from which it was originally derived. This showed an approximate 10 percent displacement in contour location overall. The DEM can be validated only against the original topographic data, not the actual land form.

MODEL INTEGRATION

Figure 3 shows how the different major modeling components are synthesized to form a predictive model of site characterization for the forest species. This is prior to the classification process for expressing the toposites in fuzzy form.

Scale and resolution issues are important in any environmental synthesis. The integration of data across scales in forestland resource assessment is discussed in Thwaites and Slater (1999). Scale definition is confined here to the concept of broad and fine scales of investigation with appropriate resolution of data. The climatic model provides a broader scale framework to the site prediction process, but the regolith-terrain analysis provides the finer scale toposite characterization. It is the site preference analysis that provides the predictive capabilities of the overall model.

One of the main reasons for using digital classification techniques is the ability to implement *a posteriori* classification, i.e., "classify last." The identification and use of individual regolith-terrain attributes focuses on what is measurable or estimable without relying on, and being influenced by, *a priori* generic soil or site classification systems, such as soil "types" or geological "formations." No *a priori* classification of sites (e.g., by soil

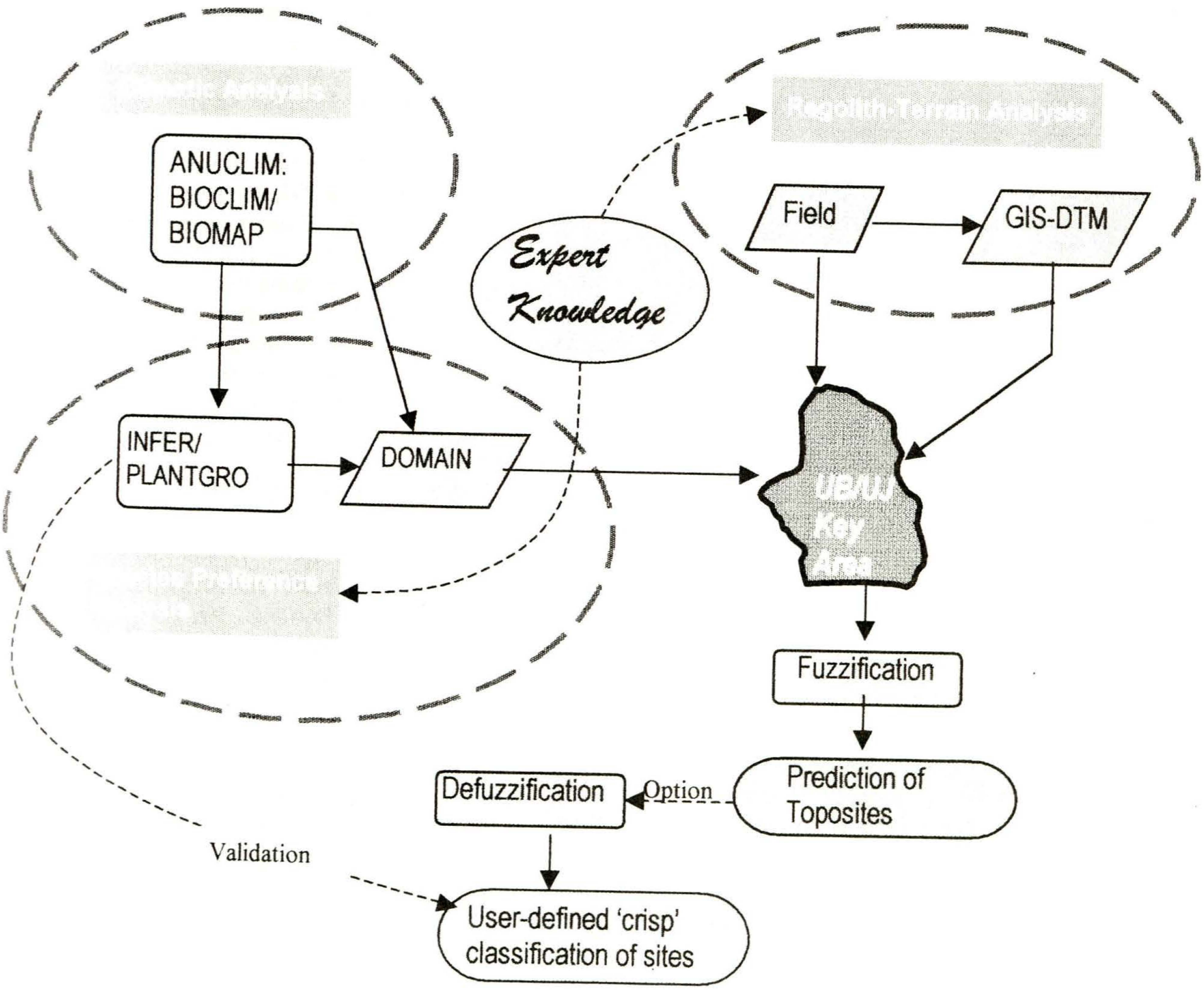

Climatic Analysis
ANUCLIM:
BIOCLIM/
BIOMAP
Expert
Knowledge
Regolith-Terrain Analysis
Field
GIS-DTM
INFER/
PLANTGRO
DOMAIN
Species Preference Analysis
UB/UJ
Key
Area
Fuzzification
Prediction of
Toposites
Option
Defuzzification
Validation
User-defined 'crisp'
classification of sites

Figure 3.— *Integration of the modeling components to create a site-species matching methodology.*

type, land type, ecological type, ecounits) has been involved in the process of this spatial model development. Generic and technical classification systems only dictate the type of data to be collected and how the data is interpreted if they are applied *a priori* to the model being developed. An *a posteriori* application of a classification system using the attribute data gained during the modeling process has more relevance to the purpose of the exercise, and can be more explicit. One such approach, which is favored here, is the use of fuzzy systems theory (see Burrough *et al.* 1992, Thwaites and Slater 1999)

Fuzzy systems are an alternative to "crisp" set membership in classification. Crisp sets operate through binary logic (i.e., True/False) whereas fuzzy logic allows for tri-valued logic (e.g., True/Possible/False). It thereby accommodates imprecision and uncertainty in complex data by invoking functions of "possibility" rather than "probability." The output can be expressed in a series of raster-format plots that relate to the classification of each toposite variable (e.g., plots of shallow, deep, and very deep regolith classes), or combined variable classes can be plotted that are relevant to specific characterization requirements of the toposites (e.g., regolith depth, soil moisture holding capacity). Optionally, these combined classes can then be defuzzified to recreate crisp classes of site quality (e.g., suitability classes—low, medium, high—for each species performance). These then can be expressed as conventional choropleth maps (polygonal units representing classes delineated by well-defined boundaries).

CONCLUSION

The methodology outlined here uses digital terrain analysis in combination with conceptual modeling, within a GIS framework, as an explicit and adaptable approach to site attribute prediction. The major advance of this process is its explicit nature by discerning the relevant attributes that characterize sites for native forest species planting. Unlike traditional soil and site survey and mapping methods, it can be replicated: results are reproducible, and can be subsequently enhanced by further iteration.

Regolith-terrain attributes are used to determine toposites both from field analysis and digital terrain analysis. These measured and generated data must be fitted into conceptual models of the landscape, which cannot be produced without expert knowledge and local wisdom. This is a key aspect of the process. Knowledge-based data (or "soft data") are synthesized with the field data and computer-generated data in a logical and methodical manner through the framework of these conceptual regolith-terrain and site suitability models.

Several computer models are used in combination to reach the desired outcome for a thorough procedure that attempts to overcome the inevitable lack of relevant data at the appropriate scale or resolution. In the case of the climatic surface model, BIOCLIM, and the terrain derivatives model, TAPES-G, the required data are generated to the best possible resolution. Combined with the site-species analysis from previously recorded field data through Plantgro and Infer, and limited field data forming conceptual regolith-terrain models (with the aid of geological and soil maps), a sophisticated picture emerges without lengthy and costly new data acquisition.

The initial work matches toposites to species using the Plantgro output files within the broad climatic stratification of the species, and then the soil map information in conjunction with the conceptual topographic regolith-terrain models. Future work will focus on spatial predictions of regolith-terrain characteristics for potential toposites from the DTM. These are then combined with the species profile information created for Plantgro, particularly the climatic envelopes defined through a BIOCLIM analysis.

ACKNOWLEDGMENTS

This work is being supported as a subproject of Project 4.1 "Ecology and Silviculture of Sustainable Timber Production" in the Australian Co-operative Research Center for Tropical Rainforest Ecology and Management (CRC-TREM). I would like to thank Professor Geoff McDonald of the Department of Geographical Sciences and Planning, and Associate Professor David Lamb of the Department of Botany, both at the University of Queensland, St. Lucia, Queensland, Australia, for reviewing earlier drafts of this paper.

LITERATURE CITED

Bouma, J.; Van Lanen, H.A.J. 1987. Transfer functions and threshold values: from soil characteristics to land qualities. In: Beek, K.J.; Burrough, P.A.; McCormack, D.E., eds. Quantified land evaluation procedures. ITC Publ. 6. Enschede, Netherlands: ITC: 106-110.

Burrough, P.A.; MacMillan, R.A.; van Deursen, W. 1992. Fuzzy classification methods for determining land suitability from soil profile observations and topography. Journal of Soil Science. 43(2): 193-210.

CRC-TREM. 1998. Annual report of the Cooperative Research Center for Tropical Rainforest Ecology and Management (CRC-TREM) 1996-97. CRC-TREM. Cairns, QLD: James Cook University.

El-Swaify, S.A.; Yakowitz, D.S., eds. 1998. Multiple objective decision making for land, water, and environmental management. In: Proceedings of the 1st International conference on Multiple objective decision support systems (MODSS) for land, water and environmental management: concepts, approaches, and applications; 1996 September; Honolulu, HI. Boca Raton, FL: Lewis Publishers.

Hackett, C. 1995a. A study of forest scientists' perceptions of trees' environmental relationships: implications for predicting growth. In: Booth, T.H., ed. Matching trees and sites: proceedings of an International workshop; 1995 March 27-30; Bangkok, Thailand. ACIAR Proc. No. 63. Canberra, ACT: ACIAR: 77-83.

Hackett, C. 1995b. INFER: an expert system for estimating the environmental relationships of plants from the conditions they experience. Unpublished report. Griffith University, QLD.

Hackett, C.; Harris, G. 1996. Plantgro: a software package for the prediction of plant growth. v.2.1 for DOS. Brisbane, QLD: Griffith University.

CRES. 1996. TAPES-G: a grid-based terrain analysis program for the environmental sciences. CRES. Canberra: ANU.

Laffan, M.D. 1988. Soils and land use on the Atherton Tableland, North Queensland. CSIRO Division of Soils, Soils and Land Use Series 61. Canberra, ACT: CSIRO.

Lane, L.J.; Ascough, J.C.; Hakonson, T.E. 1991. Multiobjective decision theory - decision support systems with embedded simulation models. In: Irrigation and drainage proceedings; 1991 July 22-26; Honolulu, HI. Honolulu, HI: IR Division, American Society Civil Engineers: 445-451.

Malcolm, D. 1999. Soil survey of Atherton Tablelands, Queensland Department of Natural Resources, Brisbane, (in press).

McMahon, J.P.; Hutchinson, M.F.; Nix, H.A.; Houlder, D.J. 1997. ANUCLIM 1.2 user guide, CRES. Canberra: ANU.

Moore, I.D.; Gessler, P.E.; Nielsen, G.A.; Petersen, G.A. 1993. Soil attribute prediction using terrain analysis. Soil Science Society of America Journal. 57: 443-452.

Sneddon, A. 1997. The use of climatic and growth characteristics to match selected native rainforest species to rehabilitation sites in north Queensland. Brisbane, QLD: The University of Queensland. Unpublished Honours thesis.

Thwaites, R.N. 1999. Biodiversity - geodiversity - soil diversity: towards a spatial understanding of soil in ecological studies of the forest landscape. Journal of Tropical Forest Science (in press).

Thwaites, R.N.; Slater, B.K. 1999. Forestland Resource Assessment: towards an explicit, multiscale approach. Journal of Forest Ecology and Management (in review).

Inventory Applications in the Management and Monitoring of Natural Resources

Can the Functional Stability of Forest Ecosystems be Evaluated from the Spatial Analysis of Stands? A Case Study from the Bialowieza Primeval Forest (Poland)

Andrzej Bobiec

Abstract.—Variability of external and internal factors entails specific spatial patterns and functional dynamics of communities. The study of the oak-lime-hornbeam (*Quercus robur-Tilia cordata-Carpinus*) forest in the Bialowieza Primeval Forest supports the concept of silvatic unit, determining the minimal structural area. To find out if the dynamics of a stand can be inferred from its spatial pattern, and to compare the structural properties of natural and managed hardwoods, detailed mapping of developmental phases in natural and managed stands was performed. While the mosaic composition in Bialowieza National Park indicates a stable character of the natural oak-lime-hornbeam forest, the managed forest reveals a considerable deficit of optimal and senescent phases and simplification of the mosaic texture. An absolute ban on cutting in remaining old-growth stands should be a basic rule for restoration management.

MOSAIC STRUCTURE, AN INHERENT FEATURE OF FOREST COMMUNITIES

Complexity of Natural Systems Makes Biodiversity

Composition, spatial structure, and dynamics are three aspects of biodiversity (Crow *et al.* 1994, after Roberts and Gilliam 1995). Any particular biological community is not only an assembly of components, but also a structural and dynamic system. Both external static factors (climate, slope, bedrock, etc.), and biotic components (species) will determine the spatial structure of a community and its dynamics. Also, the influence of external dynamic factors, such as windfalls, heavy snow, and fire, depends on species composition. On the other hand, a considerable modification of spatial pattern or dynamics of the system may lead to compositional changes. For instance, the alteration of natural dynamics in the Bialowieza Primeval Forest through forest management has resulted in a significant increase in fast-growing pioneer species there.

Dynamics and Structure: Inseparable Aspects of Forest Communities

A good example of mutual relationships of species composition, spatial structure, and dynamics is a forest community with trees as prominent components. Trees influence the lower vegetation through overshading (e.g., Beatty 1984, Tyler 1989), supplying differentiated litter (Pallant and Riha 1990, Peterson and Campbell 1993, Peterson and Facelli 1992), influencing chemical properties of stemflow and canopy throughfall (Boerner and Koslowsky 1989, Koch and Matzner 1993), and creating gaps (e.g., Clebsch and Busing 1989, Cho and Boerner 1991, Kubota 1995, Kuuluvainen 1994). The most common disturbances in the natural forest that determine the ecosystem's dynamics are windfalls (e.g., Stone 1975, Beatty 1984, Falinski 1986, Ulanova 1991). The annual number of wind-blown trees (>7 cm dbh) in the rich deciduous communities of oak-lime-hornbeam (*Quercus robur-Tilia cordata-Carpinus betulus*) forest in the Bialowieza National Park (BNP) ranges from 200 to 450 per 100 ha (Falinski 1986). With its superficial root system, spruce (*Picea abies*) is recognized as the species most prone to windfalls (Falinski 1986).

Under natural conditions, a community-specific pattern of structure and dynamics should develop. The most conspicuous structural feature of natural forests is the mosaic of regeneration units or eco-units (Oldeman 1983). The community of oak-lime-hornbeam forest is a collection of patches, representing different phases of stand development after disturbance. Dynamics and structure of stands are of great interest to ecologists and foresters, but because of methodological difficulties, the two aspects have often been treated separately. On the one hand, stand measurements led to stand development models with defined phases (Leibundgut 1959), neglecting, however, the spatial distribution of eco-units. On the other hand, most descriptions of forest communities are based on observations and measurements carried out in so-called "representative" plots. Figures reported by many authors indicate that the plots (phytosociological releves or structural plots) usually avoided gaps or larger assemblages of young trees and represented mainly the optimal (or biostatic) phase (e.g., Falinski 1986;

Senior Researcher, Bialowieza National Park, 17-230 Bialowieza, Poland.

Sokolowski 1980, 1993). Two opposite, but complementary, approaches to forest dynamics have been developing: simulation and description. The first, based on data concerning functions and physiological reactions of particular components of ecosystem, aims at construction of a computer model, that simulates the functions of the natural system (like JABOWA and derivatives; Botkin *et al.* 1972, Fulton 1991, Shugart 1984). The second approach aims at a steady improvement of tools of forest description, enabling a better interpretation of observed phenomena and the role of different components of a community (e.g., SILVI-STAR; Koop 1989).

The Bialowieza Primeval Forest as a Reference Site

Unlike tropical rain forests and remote taiga, where the mosaic structure of a community stand[1] can still fully develop (e.g., the mosaic investigation in French Guyana forest; Pelissier and Riera 1993, Riera 1995), there are few natural lowland forests left in the temperate zone of the Northern Hemisphere. In Europe, the only exception is the 47 km^2 of the strict nature reserve of BNP, the best preserved part of the Bialowieza Primeval Forest (BPF), northeastern Poland (Falinski 1986).

Forestry management, an activity focusing on trees, modifies stand structure and dynamics. The biggest changes can be observed when natural old-growth is cut and replaced by plantation. In Europe, BPF offers an exceptional opportunity to directly compare recently managed forest with preserved natural communities. The information received from the comparative studies provides a background for decisions and practical measures in the field of restoration management and nature conservation.

General Physiographic Data

The BPF (52° 43'N, 23° 50'E) is the best preserved lowland forest in the European temperate zone. Abiotic conditions in the forest are: (1) the influence of a continental climate (mean annual precipitation 641 mm, ranging from 426 to 940 mm, 85 percent as rain; mean annual temperature 6.8 °C, ranging from 5.1 to 8.8 °C, with the mean temperature ranging from 15.2 to 21.6 °C in July and from -13.4 to 1.8 °C in January; Olszewski 1986, the meteorological data from 1948 to 1983), (2) the old post-glacial formation (vast plains with altitudes ranging from 134 to 202 m above sea leavel), and (3) the watershed location (dependence on precipitation water; Falinski 1986).

Historical Traces

Protected since the 15th century as a royal hunting ground, the 1,500-km^2 BPF remained preserved until World War I (1914-1918), when intensive timber exploitation began. The most famous part of the forest is the strictly protected nature reserve of BNP (47 km^2), established in 1921 (fig. 1). Since then any commercial activity in BNP has been forbidden, except for limited tourism. Most of the area (ca. 1,200 km^2) was commercial forest (CF) until World War II. In 1945, the BPF was split into a Polish part (ca. 600 km^2), where timber exploitation had been continued, and a Soviet (today Belorussian) one, preserved as a hunting grounds.

In the Polish forest, the negative effects of the large clear-felling system forced the forestry authorities to change management methods in the late 1970's. The principle of the new forestry rules (presented as sustainable or multifunctional forestry) was reduction in the size of clearcuts to 0.25 ha. There was an increasing awareness of the role of natural regeneration, albeit planting remained the main reforesting method. As a result, the commercial forest (CF, ca. 80 percent of the Polish part of BPF) constitutes a patchwork of even-aged, usually single-species plantations; isolated remnants of natural and seminatural stands (approximately 20 percent of CF); and large areas of 60- to 80-year-old pioneer, mainly birch stands, that developed spontaneously on the clear-felling areas left without artificial reforestation.

The Main Focus: Oak-Lime-Hornbeam Forest

The predominant community of BPF is oak-lime-hornbeam forest (*Tilio-Carpinetum*), occurring in three closely related variants: *typicum* (on slightly wet sites, with low participation of maple in the stand layer and nitrophilous species in the herbaceous layer, as well as with poor geophyte flora), *caricetosum* (on wetter sites, with a considerable portion of *Carex remota* in the herbaceous layer) and *stachyetosum* (the richest variant, with significant participation of maple in the stand layer and nitrophilous species with *Stachys sylvatica* and geophytes in the herbaceous layer, Sokolowski 1993). It primarily occupies the ground moraine plains formed by boulder clay. Under the conditions of runoff-gleyey type of water circulation, the mesotrophic leached brown soils (browned lessive soils) were established (Kwiatkowski 1994). Originally, the oak-lime-hornbeam forest occupied about 45 percent of today's area of the Polish part of BPF, and it still remains the major community type in the restricted area of BNP. Rich in species, the forest's prominent components are hornbeam (*Carpinus betulus*), lime (*Tilia cordata*), maple (*Acer platanoides*), spruce (*Picea abies*), and pedunculate oak (*Quercus robur*). The most common shrub is hazel (*Corylus avellana*), sometimes overshading entire gaps. The most influential

---

[1] *Futher called "mosaic," which corresponds with "silvatic mosaic" by Oldeman (1990).*

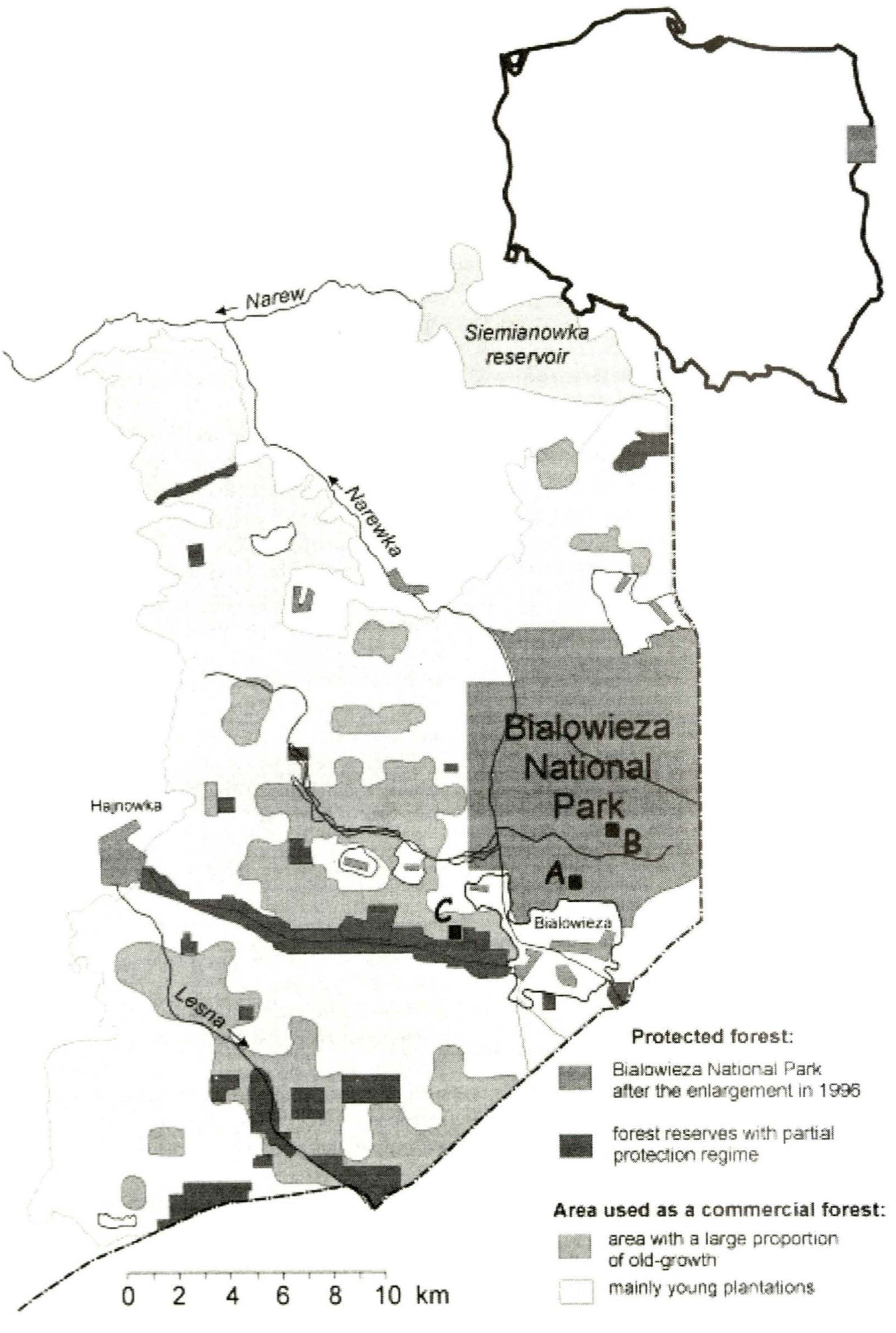

Narew
Siemianowka reservoir
Narewka
Bialowieza National Park
B
A
C
Hajnowka
Bialowieza
Lesna
0 2 4 6 8 10 km
Protected forest:
Bialowieza National Park after the enlargement in 1996
forest reserves with partial protection regime
Area used as a commercial forest:
area with a large proportion of old-growth
mainly young plantations

Figure 1.—*Study area location: Polish part of the Bialowieza Primeval Forest with the Bialowieza National Park. Black squares with letters A, B (natural forest—BNP), and C (commercial forest—CF) represent 25-ha plots, where mapping of silvatic mosaic was performed.*

dynamic factors in this almost non-flammable forest—namely tree aging, diseases and death, windfalls, and outbreaks of insects—lead to structural heterogeneity.

Definition and Description of Developmental Phases

Several developmental phases were proposed by Leibundgut (1959) and reviewed by Miscicki (1994). On the basis of preliminary observations of natural deciduous forest in BNP and tree measurements in sample plots (900-1,200 m^2 in young homogeneous stands and 2,500-5,000 m^2 in heterogeneous old growth, arbitrarily distributed in the most "typical" fragments of the forest representing pre-defined developmental phases), the following phases were distinguished:

1. Young phase (Y): Averaged data describing the phase: 25 trees per 100 m^2; dbh from 1 to 15 cm; height up to 10 m; most trees are 10-25 years old; very dense, single layer, usually established in larger gaps; floor vegetation weakly developed due to poor light conditions; usually large amount of partly decayed woody debris; dominating species at this stage of *Tilio-Carpinetum* forest are hornbeam and lime.
2. Pole phase (P): 10 trees per 100 m^2; dbh 10-30 cm; height up to 25 m; 25-40 years old; usually developed from Y, single layer or with gradually disappearing subordinated layer of outcompeted trees; full canopy coverage prevents the development of floor vegetation; woody debris less abundant and more decayed.
3. Young optimal phase (P+): 6.5 trees per 100 m^2; dbh 25-40 cm; height up to 35 m; 40-60 years old; usually single-layer cohorts of lime; emerging gaps in the canopy coverage allow better development of the floor vegetation; quantity of woody debris depends on events in neighboring eco-units.
4. Optimal phase (O): 4.5-6.5 trees per 100 m^2; dbh 2-70 cm, with individual trees exceeding 150 cm; height up to 42 m (lime, oak, and ash - *Fraxinus excelsior*) and 55 m (spruce); 60-200 years old (some trees may exceed 450 years); complex vertical structure, usually three distinct layers of trees with the intermediate one being the most dense; highly variable canopy covers 75-100 percent of the area and contributes to the uneven development of floor vegetation and recruitment of new saplings from the seedling bank; amount of dead wood is variable in space.
5. Terminal phase (T): Disconnected canopy coverage, the complex of small gaps and solitary, mainly aging, sick, or dying trees; with poor renewal or the brushes of saplings steadily grazed by ungulates; abundant herbaceous layer; usually great amount of woody debris.
6. Regeneration phase (R): 15-20 trees per 100 m^2; dbh of most of trees from 2 to 25 cm, with few old and large specimens, whose canopies cover less than 50 percent of the area; highly variable vertical structure (tree heights from 4 to 40 m) indicates a long-lasting renewal period; R can seemingly grow optimal or steadily homogenize and transform into P.

According to the terminology of Oldeman (1990), phases Y, P, P+, and R correspond to the "aggradation phase," phase O to the "biostatic phase," and phase T is an equivalent of the "degradation phase." Because our measurements neglected trees below 1.3 m in height, the present classification does not distinguish the "innovation phase," defined by Oldeman (1990). As long as young saplings do not reach the measurement threshold, the open units are being classified as either gaps (G) or phase T.

RESULTS: MAPPING AS A BASIC TOOL IN MOSAIC APPROACH

Mapping for Managing

The main criterion used by the routine forest inventory, carried out in the BPF in 1989-1993, was the forest site classification, based on edaphic and humidity site characteristics. Within every forest subcompartment, representing the forest type, relascope (Bitterlich 1947) samplings (one per 0.84 ha on average) were performed in order to describe the stand characteristics (species composition and percent canopy coverage, age of the dominant species). The survey resulted in a map of stands at the scale of 1:10000 (fig. 2). This kind of data provides important background information on the forest variability determined by abiotic and static factors. However, it is not sufficiently informative in terms of stand structure and dynamics.

Mapping for Learning: The Field Example

To approach the texture (variability of eco-unit sizes, grain size structure) of the oak-lime-hornbeam forest community, detailed mapping (based on preliminarily described characteristics of the developmental phases) of 25-ha plots representing oak-lime-hornbeam forest was performed. Preliminary observations and trials of direct mapping of developmental phases in the field showed patches delimitation as a most difficult and unreliable operation. The use of regular 10 x 10-m pixels (100-m^2 units) avoids the dilemmas accompanying the drawing of arbitrary limits. The decision is restricted to the classification of pixels, based on the above listed characteristics of the developmental phases (fig. 3).

The pattern revealed by the developmental phases shows no relationship with the areas depicted by the techniques used during the forest inventory survey (figs. 2 and 3). There is a striking divergence of the spatial pattern determined by the forestry management in CF from the

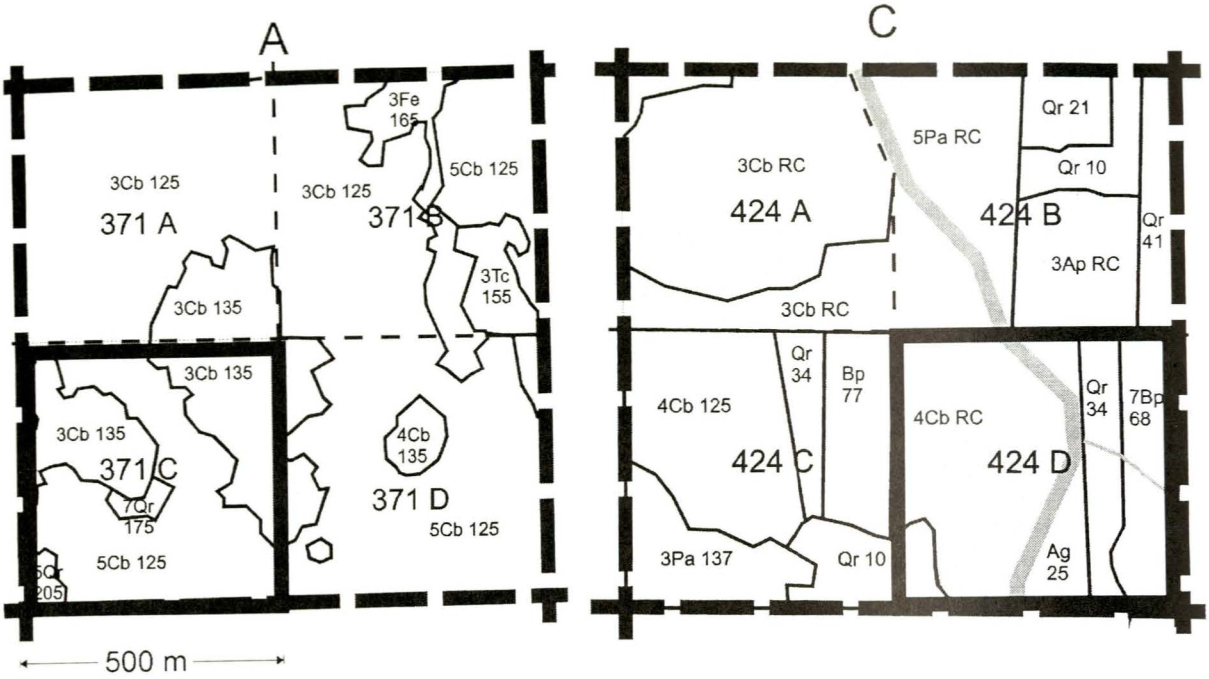


Figure 2.—*Two fragments of the map produced by the forest inventory in 1989-1993, representing natural and managed forest (letters A and C- the names of plots refer to the map in figure 1). Numbers before the abbreviations of dominant species names stand for their relative participation in stand (10=100 percent). Numbers after the names correspond with the average age of a dominant species. The gray line denotes roads, and the gray-striped area refers to the so-called "regeneration class" (RC), where cutting began recently. Ag* - Alnus glutinosa, *Ap* - Acer platanoides, *Bp* - Betula pendula, *Cb* - Carpinus betulus, *Pa* - Picea abies, *Qr* - Quercus robur.

mosaic developed under natural conditions in BNP. The discrepancy is in both the mosaic composition (percent participation of particular phases) and its texture. The most conspicuous compositional difference is a total lack of phase T and a clearly lesser participation of phase O (20 percent) in the plot representing CF in comparison with the plots in BNP (33 and 40 percent). In the natural oak-lime-hornbeam forest, the area covered by gaps and phase T is similar in size to the area occupied by stands of the future: phases Y, P, P+, and R (table 1). The analysis of linear dimensions of the eco-units, along the rows and columns of plots, displayed two different types of distribution: (1) one-tailed, geometric distribution - referring to the plots in BNP, and (2) asymmetrical two-tailed distribution, with the extra peak at the large eco-unit classes (fig. 4).

DISCUSSION

Hierarchy of Mosaics

The investigation of stand structure, carried out in the oak-lime-hornbeam forest of Bialowieza, fully supports the concept of silvatic mosaic, as proposed by Oldeman (1990). The basic assumption is that the silvatic mosaic is a supersystem developed on a relatively homogeneous site, i.e., within the limits of a community. Its components, eco-units (regeneration units), are pieces of the area, "on which at one moment in time a vegetation development has begun, of which the architecture, ecophysiological functioning and species composition are ordained by one set of trees until the end" (Oldeman 1990, p. 165). Depending on the character of the so-called "zero event" (vast and intensive disturbance that destroys most of the stand) initializing a new eco-unit, it can develop as even-aged or uneven-aged (Oldeman 1990). In the present study, young and pole phases reveal mostly even-aged character, while the eco-units representing regeneration, optimal, and terminal phases are uneven-aged. The mosaics studied clearly differ from the forest mosaics, which reflect variability among the sites determined by the abiotic factors ("edaphic mosaic," according to Lertzman *et al.* 1996). Forest mosaics are systems of higher level organization and are composed of actual silvatic mosaics. The forestry maps prepared during the standard inventory show forest mosaics determined by the site characteristics and very general parameters describing stands as basic management units. This kind of data matches the traditional forestry approach based on strict rules of silvicultural methods and tools ascribed to a given site type. It provides, however, no information on spatial structure and dynamic trends of the community.

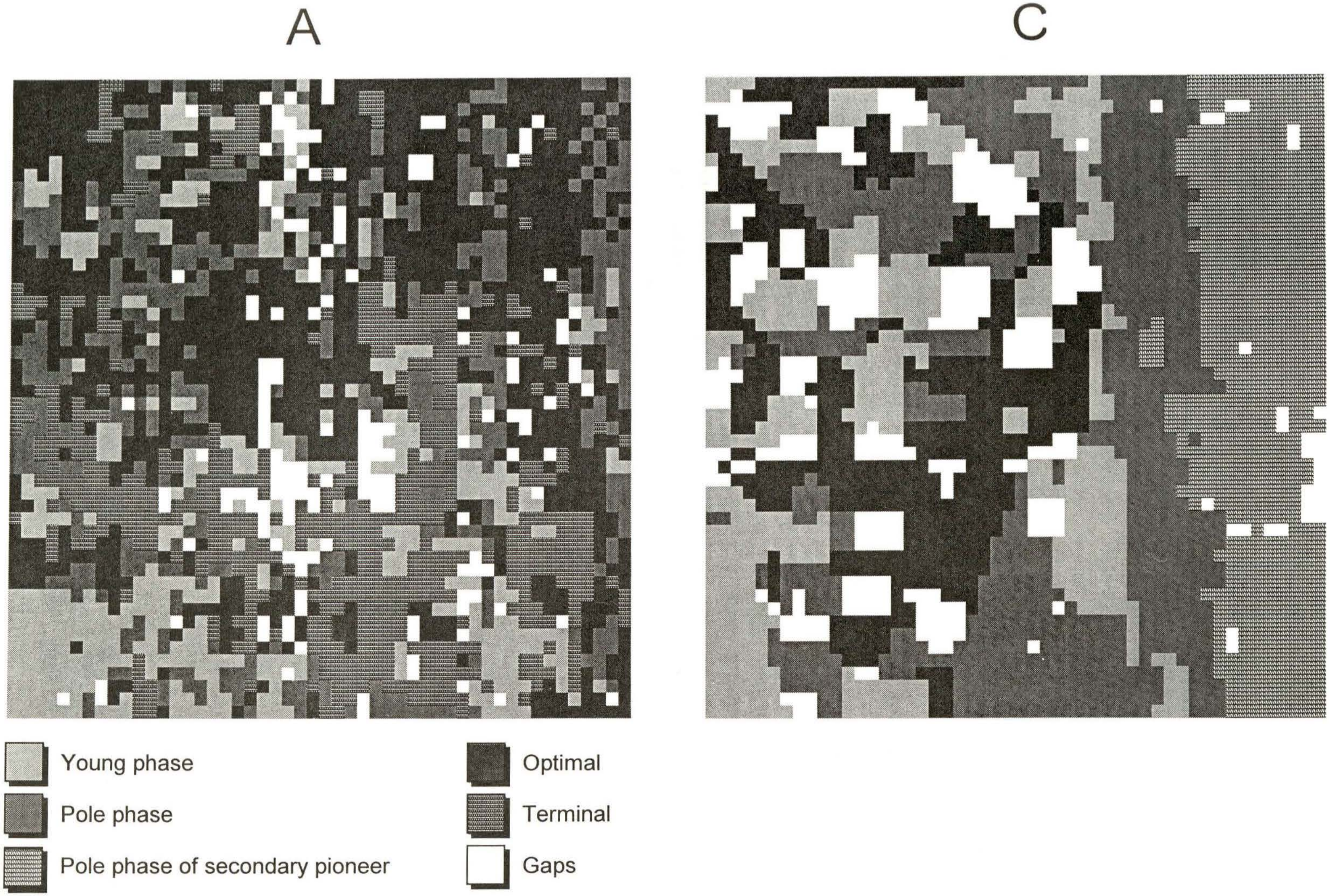

A
C
Young phase
Pole phase
Pole phase of secondary pioneer
Optimal
Terminal
Gaps

Figure 3.—*Silvatic mosaics representing natural and managed oak-lime-hornbeam forest(letters A and C- the names of plots refer to the map in figure 1).*

Table 1.—*Percentage shares of various developmental phases in three 25-ha plots investigated in the natural (A, B) and managed (C) oak-lime-hornbeam stands in Bialowieza Primeval Forest*

Developmental phase	**Study plot**		
	A	**B**	**C**
Young	16	3	18
Pole	18	19[1]	50[2]
Regeneration	—	10	—
Optimal	40	32	19
Terminal	20	20	—
Gaps	6	15	12

[1] Includes the pre-optimal phase P+.

[2] Includes pioneer secondary stand.

The Minimal Structural Area

The composition of the two 25-ha mosaics representing natural communities of the oak-lime-hornbeam forest in BNP suggests a dynamic equilibrium stage, where a considerable area of diverse, long-lasting optimal phase is accompanied by equal areas of terminal phase with gaps (stand of the past) and three young phases (stand of the future). However, taking into consideration the chaotic character of eco-unit distribution in the plots and their size variability, one must suppose that an area of 25 ha is very close to a community-specific "silvatic unit," or "minimal structural area" defined as "the minimum surface at any one site needed for all architectural growth phases of all locally possible eco-units" (Oldeman 1983, cited after Oldeman 1990, p. 388), "which are perpetually represented by forest self-regulation" (Koop 1981, cited after Oldeman 1990, p. 389).

Disturbance Factors and Mosaic Texture

The texture of the studied natural mosaic indicates the mixed character of "zero events." As expected in natural stands (e.g., Coates and Burton 1997, Lertzman *et al.* 1996), small-scale events, such as the death of a single tree or small groups of trees (caused by biotic or abiotic factors), play an important role in the development of a fine-grained mosaic. However, a wide range of sizes of eco-units showed that the "ideal" model, totally determined by only small-scale phenomena, ascribed by Oldeman (1990) to the conservationists, is not a feature of the actual community. In fact, small-scale phenomena overlap the effects of rare but high-energy events (in our case—local whirlwinds) bearing large eco-units. The observed variety of eco-units in the natural forest secures a wide range of microenvironments suitable for different

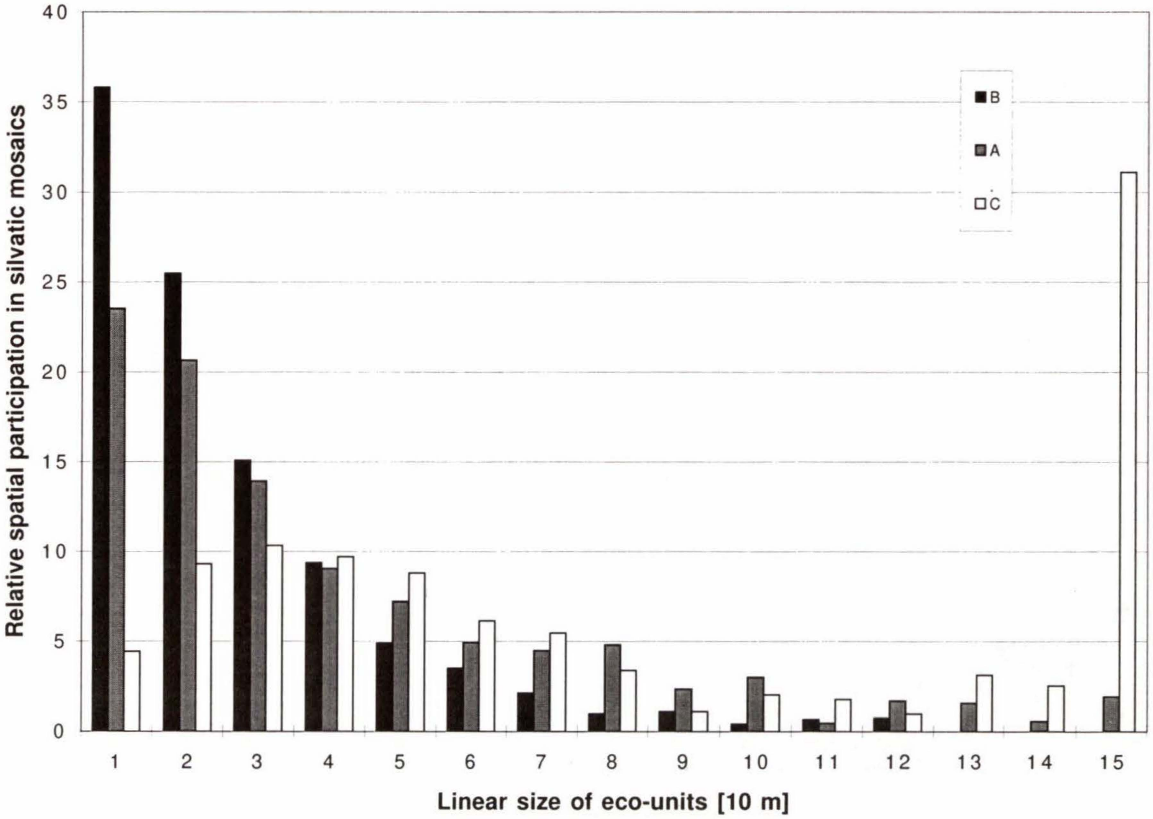


Figure 4.—*Comparison of the mosaic pattern between natural (A and B) and managed (C) stands reveals a dramatic reduction of the fine-grained texture in consequence of the forest management (letters A, B, and C- the names of plots refer to the map in figure 1).*

plant, fungi, and animal species. On the basis of a thorough experimental approach, Coates and Burton (1997, p. 349) stated that "each size of gap has a characteristic combination of light regimes, which are correlated with a number of other microclimate attributes which collectively determine vegetation responses." It must be kept in mind, however, that—as mentioned earlier—gap dynamics remains in a feedback relationship with other features of a community, particularly with tree species composition. Gap dynamics seems to be characteristic of communities in which the tree crown architecture prevents light from penetrating to the ground and inhibits continuous stand renewal beneath the canopy. The model probably does not apply to riverine ash-alder or swamp alder forest communities that lack closed canopies.

When Multifunctional Forestry Jeopardizes Nature Conservation

The studied fragment of the managed forest revealed a clear divergence from the natural pattern found in BNP in terms of mosaic composition and texture, albeit it has been managed according to the current rules of pro-ecological and multifunctional forestry (Anonymous 1997). In practice, pro-ecological forestry means a mere set of techniques and tools realizing an ideal model of multifunctional forest. The main goal of "good forestry" is to diversify the stands, oversimplified due to long-lasting schematic treatment, and to increase the biodiversity standards. An obvious contradiction emerges, however, between the biodiversity protection postulate and the actual effects of multifunctional forestry, when implemented in the remnants of natural forest. There, the components of biodiversity most at risk are the species characteristic of late successional stages, i.e., old growth (Buchholz and Ossowska 1995, Pielou 1995). At a landscape level, old growth is so rare that this is worth serious consideration.

Practical Recommendations

According to the Forest Practices Code of the British Columbia Forest Service (Fenger 1996), two criteria must be met to conserve biodiversity: (1) the old-growth forest should cover at least half the area relative to that occurring naturally, and (2) no more than twice the area in a landscape unit should be forest of less than 40 years compared to that occurring naturally. The retained fragments of old growth should be as large as possible, because patches of old-growth forest smaller than 600 m in diameter do not contain interior forest habitat but consist entirely of edge habitat (Fenger 1996). Applied to the situation of the managed part of the Bialowieza Forest, it indicates a basic tenet of future management: the unquestionable sanctity of all remaining old growth, in order to retain a continuous matrix of late successional stages. Stands must be allowed to transform freely into the terminal phase or gradually renew in small gaps. All the forestry management with logging should be aimed at restoring the natural mosaic pattern. It can be done partially through group cuttings carried out in large fragments of even-aged young or pole phases, thus improving the texture of the mosaic. Future management of the Bialowieza Primeval Forest, besides the structural and dynamic aspects of the forest, should consider the ecological characteristics of particular developmental phases. For instance, by establishing oak plantations, forest management caused considerable changes in soil and field-layer vegetation (Bobiec 1998). The felled-tree openings being reforested immediately do not play the same ecological role as some long-lasting gaps in natural forests. Even old-growth patches left in the CF differ from those in BNP, because of the removal of dying trees and coarse woody debris.

CONCLUSIONS

On the basis of the present material, the following conclusions can be drawn:

1. The silvatic mosaic (as defined by Oldeman 1990), defined by the texture (sizes of eco-units) and relative participation of different developmental phases, is a feature inherent to a given forest community. It develops as an effect of interactions between internal factors, such as tree regeneration, growing, and aging processes, and external factors, such as wind-blows, heavy snow, etc.
2. The mosaic composition of natural fragments of the oak-lime-hornbeam forest in BNP indicates that the silvatic mosaic has reached the equilibrium stage: the optimal (biostatic) phase occupies 34-40 percent of the area, the area of senescent phases is similar to that of the young ones.
3. In Bialowieza, the forestry management of oak-lime-hornbeam forest has led to a sharp discrepancy between the mosaic pattern and composition in protected and exploited parts of the Forest.
4. The idea of multifunctional forestry does not meet the standards of biodiversity conservation on the grounds of 600-km^2 woodlands, where patches of old-growth forest are scarce.
5. To retain a continuous matrix of late successional stages, the unquestionable sanctity of all the remaining old growth must be the basic tenet of any future management of BPF and other ancient woodlands. Any logging should be aimed at restoring of the natural mosaic pattern. It can be done partially through group cuttings carried out in large fragments of even-aged young or pole phase, thus improving the texture of the mosaic and reducing the risk of future large-scale disturbances.
6. The standard methods of forest inventory do not capture the complex nature of the natural forest. The

mosaic approach appears to be an appropriate and efficient tool in the investigation of forest community structure in space. Developed and improved methods, possibly with use of aerial photography, should be basic tools in monitoring forest dynamics and in designing management and conservation measures.

ACKNOWLEDGMENTS

My special thanks are due to Haico van der Burgt, Jos Haga, and Casper Zuyderduyn—forestry students from **'t Vanck**, Helicon Opleidiningen (Velp, The Netherlands)—for their excellent field work. The study was part of the research project 6P04F054 12 financed by the Committee of Scientific Research (KBN). I am grateful to the organizers of this Conference for waiving the participant fee and to the Batory Fund for financing the costs of my trip.

The following people reviewed this manuscript: Richard Busing, Pacific Northwest Research Station, Forestry Sciences Laboratory, Corwallis, Oregon, USA; Rey Offren, Department of Geography, University of Auckland, Auckland, New Zealand; and Berthold Traub, Swiss Federal Institute for Forestry, Snow, and Landscape Research WSL, Bmensdorf, Switzerland

LITERATURE CITED

Anonymous. 1997. Silvicultural and protective rules in forest ecosystems of the Forest Promotional Complex "Bialowieza Primeval Forest." Bialystok: Regional Board of State Forest in Bialystok. 25 p. (in Polish)

Beatty, S.W. 1984. Influence of microtopography and canopy species on spatial patterns of forest understory plants. Ecology. 65(5): 1406-1419.

Bitterlich, W. 1947. Die Winkelzählmessung. Allgemeinne Forst-und Holzwirtschaftliche Zeitung. Wien, 12/13.

Bobiec, A. 1998. The mosaic diversity of field layer vegetation in the natural and exploited forest of Bialowieza. Plant Ecology. 136: 175-187.

Boerner, R.E.J.; Koslowsky, S.D. 1989. Microsite variations in soil chemistry and nitrogen mineralization in a beech-maple forest. Soil Biology and Biochemistry. 21: 795-801.

Botkin, D.B.; Janak, J.; Wallis, J. 1972. Some ecological consequences of a computer model of forest growth. Journal of Ecology. 60: 849-872.

Buchholz, L.; Ossowska, M. 1995. Entomofauna of dead wood - its biocenotic meaning in forest environments and possibilities and problems in its protection. Przeglad Przyrodniczy. 6(3/4): 93-105. (in Polish with English summary)

Clebsch, E.E.C.; Busing, R.T. 1989. Secondary succession, gap dynamics, and community structure in a southern Appalachian cove forest. Ecology. 70(3): 728-735.

Cho, D.-S.; Boerner, R.E.J. 1991. Canopy disturbance patterns and regeneration of *Quercus* species in two Ohio old-growth forests. Vegetatio. 93: 9-18.

Coates, K.D.; Burton, P.J. 1997. A gap-based approach for development of silvicultural systems to address ecosystem management objectives. Forest Ecology and Management. 99: 337-354.

Crow, T.R.; Haney, A.; Waller, D.M. 1994. Report on the scientific roundtable on biological diversity convened by the Chequamegon and Nicolet National Forests. Gen. Tech. Rep. NC-166. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station.

Falinski, J.B. 1986. Vegetation dynamics in temperate lowland primeval forests. Ecological studies in Bialowieza Forest. Dordrecht, Boston, Lancaster: Dr W. Junk Publishers. 537 p.

Fenger, M. 1996. Implementing biodiversity conservation through the British Columbia Forest Practices Code. Forest Ecology and Management. 85: 67-77.

Fulton, M.R. 1991. A computationally efficient forest succession model: design and initial tests. Forest Ecology and Management. 42: 23-34.

Koch, A.S.; Matzner, E. 1993. Heterogeneity of soil and soil solution chemistry under Norway spruce (*Picea abies* Karst.) and European beech (*Fagus silvatica* L.) as influenced by distance from the stem basis. Plant and Soil. 151: 227-237.

Koop, H. 1981. Vegetatiestructuur en dynamiek van twee natuurlijke bossen: het Neuenburger en Hasbrucher Urwald. Wageningen, The Netherlands: PUDOC. 112 p. (in Dutch with English summary)

Koop, H. 1989. Forest dynamics, SILVI-STAR: a comprehensive monitoring system. Berlin, Heidelberg, New York: Springer-Verlag. 230 p.

Kubota, Y. 1995. Effects of disturbance and size structure on the regeneration process in a sub-boreal coniferous forest, northern Japan. Ecological Research. 10: 135-142.

Kuuluvainen, T. 1994. Gap disturbance, ground microtopography, and the regeneration dynamics of boreal coniferous forests in Finland: a review. Annales Zoologici Fennici. 31(1): 35-51.

Kwiatkowski, W. 1994. Vegetation landscapes of Bialowieza Forest (map in scale 1:50 000 with comment). Phytocoenosis - Supplementum Cartographiae Geobotanicae. 6: 35-87.

Leibundgut, H. 1959. Uber Zweck und Methodik der Struktur - und Zuwachsanalyse von Urwäldern. Schweizerische Zeitschrift für Forstwissenschaft. 110(3): 111-124.

Lertzman, K.P.; Sutherland, G.D.; Inselberg, A.; Saunders, S.C. 1996. Canopy gaps and the landscape mosaic in a coastal temperate rain forest. Ecology. 77(4): 1254-1270.

Miscicki, S. 1994. Using developmental stages of forest stands as a basis for forest inventory. Sylwan. 138: 29-39 (in Polish with English summary).

Oldeman, R.A.A. 1983. Tropical rain forest, architecture, silvigenesis, diversity. In: Tropical rain forest: ecology and management. Oxford, England: Blackwell Scientific Publications Ltd.: 139-150.

Oldeman, R.A.A. 1990. Forests: Elements of Silvology. Berlin - Barcelona: Springer-Verlag. 624 p.

Olszewski, J.L. 1986. The role of forest ecosystems in modifying local climate of the Bialowieza Primeval Forest, as revealed by air temperature characteristics. Wroclaw - Lodz: Zaklad Narodowy imienia Ossolinskich Wydawnictwo Polskiej Akademii Nauk. 222 p. (in Polish with English summary)

Pallant, E.; Riha, S.J. 1990. Surface soil acidification under red pine and Norway spruce. Soil Science Society of America Journal. 54: 1124-1130.

Pelissier, R.; Riera, B. 1993. Dix ans de la dynamique d'une foret dense humide de Guyane Franaise. Revue d'Ecologie (Terre et Vie). 48: 21-33.

Peterson, C.J.; Campbell, J.E. 1993. Microsite differences and temporal change in plant communities of treefall pits and mounds in an old-growth forest. Bulletin of the Torrey Botanical Club. 120(4): 451-460.

Peterson, C.J.; Facelli, J.M. 1992. Contrasting germination and seedling growth of *Betula alleghaniensis* and *Rhus typhina* subjected to various amounts and types of plant litter. American Journal of Botany. 79(11): 1209-1216.

Pielou, E.C. 1995. Biodiversity versus old-style diversity. Measuring biodiversity for conservation. In: Measuring and monitoring biodiversity in tropical and temperate forests. Proceedings, IUFRO Symposium; 1994 August 27-September 2; Chiang Mai, Thailand; Bogor, Indonesia: Center for International Forestry Research (CIFOR): 5-17.

Riera, B. 1995. Role des perturbations actuelles et passees dans la dynamique et la mosaic forestiere. Revue d'Ecologie (Terre et Vie). 50: 209-222.

Roberts, M.R.; Gilliam, F.S. 1995. Patterns and mechanisms of plant diversity in forested ecosystems: implications for forest management. Ecological Applications. 5(4): 969-977.

Shugart, H.H. 1984. A theory of forest dynamics. New York: Springer. 278 p.

Sokolowski, A.W. 1980. Forest communities of North-eastern Poland. Monographiae Botanicae. 60: 3-205. (in Polish with English summary)

Sokolowski, A.W. 1993. Phytosociological characteristics of forest communities in the Bialowieza National Park. Parki Narodowe i Rezerwaty Przyrody. 12(3): 5-190. (in Polish with English summary)

Stone, E.L. 1975. Windthrow influences on spatial heterogeneity in a forest soil. Mitteil. Schweiz. Anstalt Forst. Vers. 51: 77-87.

Tyler, G. 1989. Interacting effects of soil acidity and canopy cover on the species composition of field-layer vegetation in oak/hornbeam forests. Forest Ecology and Management. 28: 101-114.

Ulanova, N.G. 1991. Vegetation mapping as a tool for detection of windfall processes in primary forest communities. Supplementum Cartographiae Geobotanicae. 3(2): 219-222.

Has Virginia Pine Declined? The Use of Forest Health Monitoring and Other Information in the Determination

William G. Burkman and William A. Bechtold

Abstract.—This paper examines the current status of Virginia, pine focusing on Forest Health Monitoring (FHM) results and using Forest Inventory and Analysis (FIA) information to determine if Virginia pine is showing a decline. An examination of crown condition data from live trees in the FHM program from 1991 through 1997 showed that Virginia pine had significantly poorer crown conditions for crown dieback and crown density. The crown variable relationships were poorer for trees that died after 1993. In addition, the numbers of Virginia pines on the FHM plots declined during the same time period, even accounting for ingrowth. FIA information across the range of Virginia pine has shown that mortality was 48 percent and removals were 92 percent of net annual growth. Virginia pine is showing a decline based on both FHM crown rating information and FIA data for removals and growth, but this is typical and expected due to the shade intolerance and short-lived nature of Virginia pine.

Virginia pine (*Pinus virginiana* Mill.) is a small to medium tree found from northern Alabama to New Jersey, growing throughout the Piedmont and lower elevations of the Appalachians (Carter and Snow 1990). It can grow in pure stands and is a major species in the Society of American Foresters cover types of Virginia Pine-Oak and Virginia pine (Eyre 1980). It is also an associate of nine other cover types. It grows well on a wide variety of soils and is usually a pioneer species on old fields, burned areas, and other disturbed sites. Being a pioneer species and shade intolerant, it generally is a transitional tree species that is replaced by more shade tolerant trees.

The Forest Health Monitoring (FHM) program began in 1990, with additional activity in the southern and mid-Atlantic areas of the US in 1991. FHM plots were installed in Alabama, Delaware, Georgia, Maryland, New Jersey, and Virginia at this time. FHM is designed to annually collect, analyze, and report on the forest conditions of the US. The basis of this information is various groups of measurements (indicators) that describe aspects of forest conditions. The current indicators that are implemented on FHM plots are tree growth, tree mortality, tree regeneration, crown conditions, damage symptoms, and ozone bioindicator plants. For more information about FHM, see Stolte (1997) or visit the FHM web site at "http://willow.ncfes.umn.edu/fhm/fhm_hp.htm".

Three crown condition variables have been shown to reflect stresses on trees: crown density, crown dieback, and foliage transparency (Cox *et al.* in preparation). These crown ratings are collected for each live tree on FHM plots with a dbh of 5.0 inches or greater. All three of these crown variables are recorded in 5 percent increments with the recorded code being the upper range, i.e., 25 is 21 to 25 percent. The value for a given tree is the value agreed to by field crew members. Crown density values for a species are generally normally distributed, while crown dieback and foliage transparency values are usually skewed toward zero. For a complete description of crown rating procedures, see USDA Forest Service (1997).

Crown density is an estimate of the amount of skylight obstructed by branches, foliage, and reproductive structures. Anderson and Belanager (1987) showed that high crown-density values were positively correlated with radial growth in loblolly (*Pinus taeda* L.) and shortleaf pines (*Pinus echinata* Mill.). Crown dieback is branch mortality that starts near the terminal and proceeds toward the trunk or at the top of a tree toward the ground. Crown dieback usually occurs in the upper part of the crown and is a symptom of various stresses on the tree, such as drought (Millers *et al.* 1992). Foliage transparency is the amount of skylight visible through the live, normally foliated portion of the crown. This measurement is an indicator of the foliage in the crown, a surrogate measure of defoliation (Millers *et al.* 1992).

As early as 1993, crown conditions in Virginia pine were identified as deviating from the trend of other pine species in the active FHM southern and mid-Atlantic states (Burkman *et al.* 1998). These authors stated that ". . . crown ratings and damage data from sample plots do not suggest any widespread decline, except for Virginia pine where crown conditions continue to decline." It is this possible decline in Virginia pine that initiated the work

---

Program Manager and Resource Analyst, respectively, USDA Forest Service, Southern Research Station, Asheville, NC, USA.

described in this paper to determine if the decline is real and what its potential causes are. The objectives of this paper are to:

1. determine if Virginia pine is experiencing a decline through the detailed analyses of FHM crown condition data, and
2. use the FHM and FIA data to offer possible explanations.

PROCEDURES

FHM plot data from Alabama, Delaware, Georgia, Maryland, New Jersey, and Virginia for loblolly, shortleaf, Virginia, and slash (*Pinus elliottii* Engelm.) pines from 1991 through 1997 were included in this study. Due to budget constraints, no data were collected in 1996. All FHM plots in these six states were installed in 1991. From 1992 through 1994, all plots were visited and the crown condition and damage symptom data were collected on all live trees. Also, any tree that died on each plot was recorded by year, but no ingrowth trees were added to the data set. In 1995, all plots were revisited and data were collected as in 1992 through 1994, but ingrowth trees were also recorded. In 1996, FHM moved from an "every plot, every year" sampling strategy to a "rotating panel" sampling scheme. In the rotating panel, a subset of the plots, one-third, was visited on a rotating format. So in 1997, only one-third of the plots were visited, but all measurements were collected and both mortality and ingrowth trees were included in the data collection effort. This sampling scheme will be continued in the future for FHM. For a complete description of this rotating panel design, please see Smith *et al.* (in review).

From the FHM data set for these years, two data sets were created:

1. A data set of all loblolly, shortleaf, Virginia, and slash pines alive in 1997 that included crown density, crown dieback, and foliage transparency for the years 1991 through 1995 and 1997, and
2. A data set of all loblolly, shortleaf, Virginia, and slash pines that died from 1993 through 1997 that included crown density, crown dieback, and foliage transparency for the years 1991 through 1995 and 1997.

Using linear regression analysis in SAS (SAS 1989), a line for each crown variable over time was fitted for each tree on each plot. The slopes of each of these lines were then organized into another data set. From this output data set of individual tree slopes, a weighted mean for each crown variable by species by plot was determined. A weighted mean was used because the number of trees per plot ranged from 1 to 58 for loblolly pine, 1 to 25 for shortleaf pine, 1 to 64 for slash pine, and 1 to 44 for Virginia pine. Each of these weighted plot means was then tested for deviation from zero by a using a standard t-test (SAS 1989). This analysis was repeated for the mortality tree data set. This analysis would not test any complex relationship, i.e., curvilinear, but tested only whether the overall trend over time was increasing or decreasing.

The interpretation of the results will vary by the crown rating variable. A positive slope for crown density means that the crown condition of the tree is improving, while a positive slope for crown dieback and foliage transparency means that the crown condition is declining.

RESULTS AND DISCUSSION

The mean crown density, crown dieback, and foliage transparency data for 1991 through 1997 for Virginia, loblolly, shortleaf, and slash pines are shown in figures 1, 2, and 3, respectively. Generally, Virginia pine had the poorest or one of the poorest plot means for all crown variables from 1991 through 1997. It is especially true for crown dieback (fig. 2) and foliage transparency (fig. 3) for all years and for crown density for most years except 1997 (fig. 2).

The results for the mean slope plot values for the live trees are contained in table 1. Virginia pine had a significant ($P = 0.05$) annual increase (declining condition) for crown dieback of almost 1 percent and it had a significant ($P = 0.05$) annual decrease (declining condition) of 1 percent for crown density. The results for shortleaf pine were non-significant ($P = 0.05$) for all three crown variables. Slash pine had significant ($P = 0.05$) improving conditions for both crown density and crown dieback. Results for all crown variables for loblolly pine were significantly declining ($P = 0.05$). This is most likely due to the large numbers of plots and trees in the data set.

The results for the trees that died after 1993 are contained in table 2. Slash pine was not included in the analysis because of the small number of plots (five) and trees (eight) in the data set. Virginia pine had a significant ($P = 0.05$) annual increase (declining condition) for crown dieback of 2.54 percent. The value for mortality trees was almost three times greater that for trees still alive in 1997. Virginia pine also had a significant ($P = 0.05$) annual decrease (declining condition) of 1.7 percent for crown density, which was almost two times greater than trees still alive in 1997. The results for shortleaf and loblolly pines were non-significant for all three crown variables.

The results for live loblolly and Virginia pine trees show that a decline is occurring with crown density and crown dieback. In general, the annual change is larger in Virginia pine than in loblolly pine. Another issue that

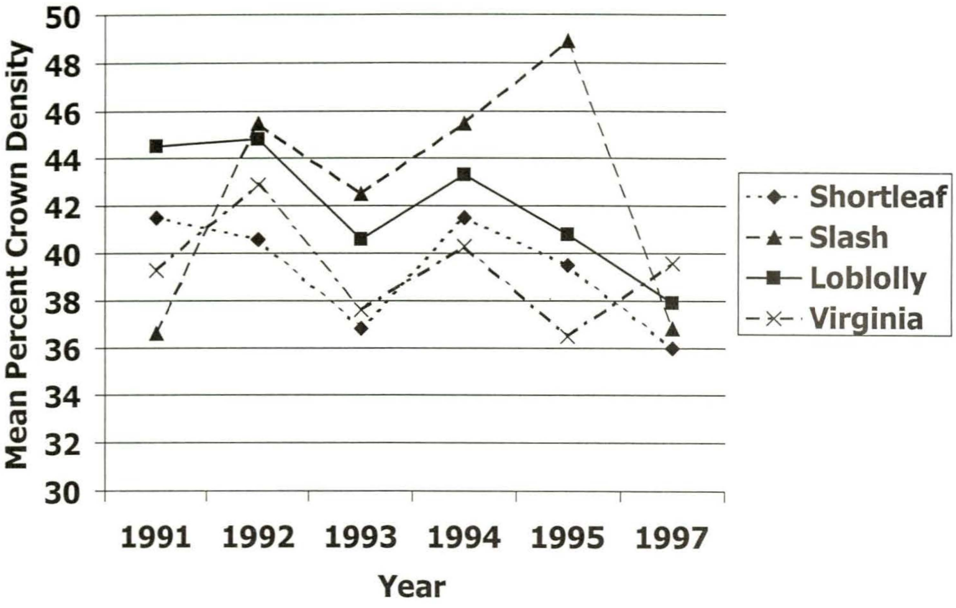


Figure 1.—*Mean crown density for shortleaf, slash, loblolly, and Virginia pines on FHM plots in Alabama, Delaware, Georgia, Maryland, New Jersey, and Virginia, 1991 through 1995 and 1997.*

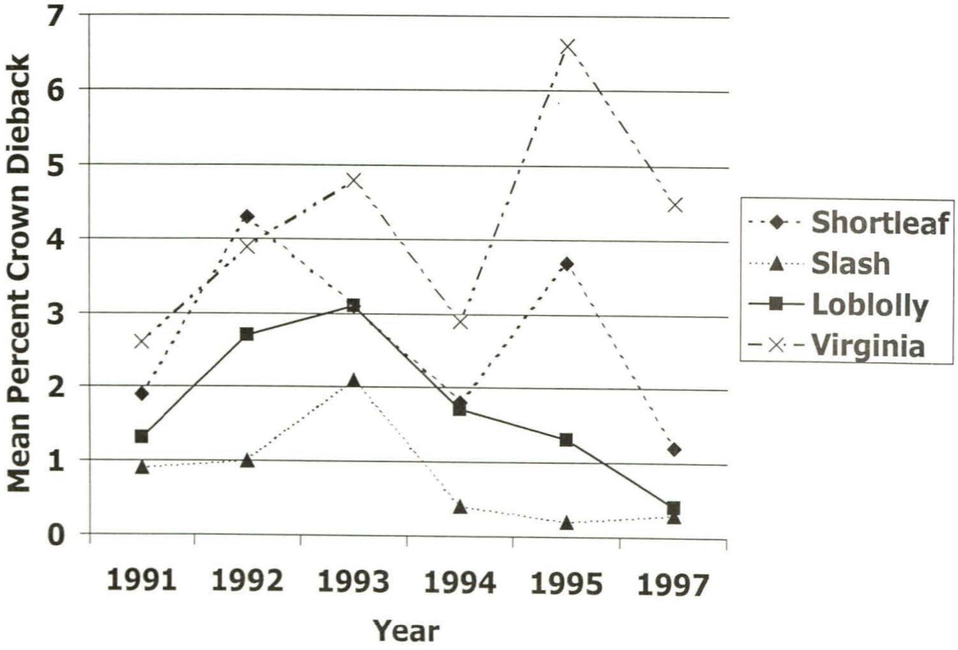


Figure 2.—*Mean crown dieback for shortleaf, slash, loblolly, and Virginia pines on FHM plots in Alabama, Delaware, Georgia, Maryland, New Jersey, and Virginia, 1991 through 1995 and 1997.*

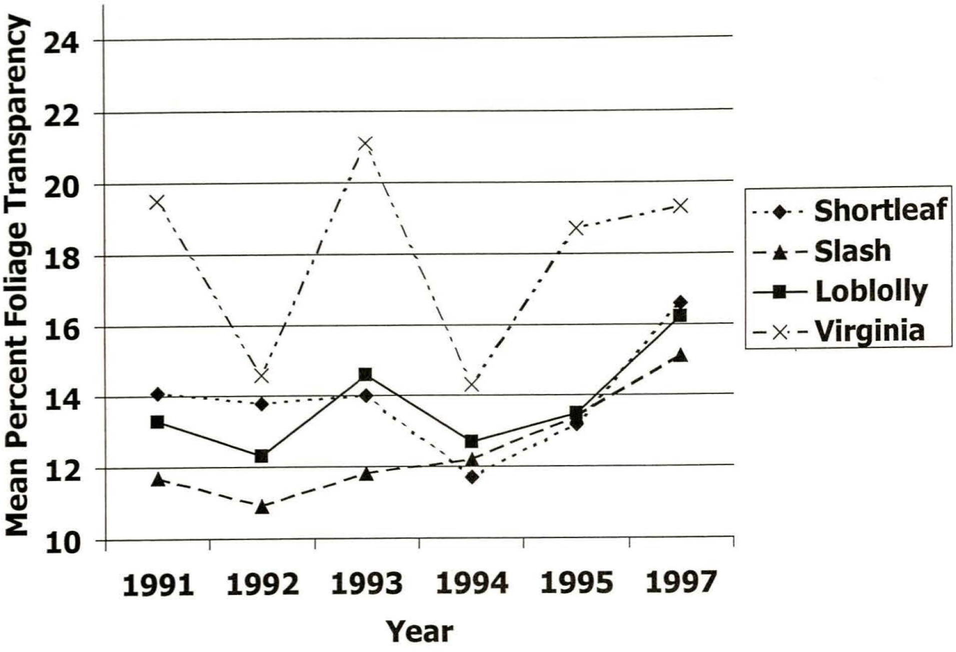


Figure 3.—*Mean foliage transparency for shortleaf, slash, loblolly, and Virginia pines on FHM plots in Alabama, Delaware, Georgia, Maryland, New Jersey, and Virginia, 1991 through 1995 and 1997.*

Table 1.—*Mean slope, probabilities, number of plots, and number of trees by pine species (shortleaf, slash, loblolly, and Virginia) and crown variables (crown density, crown dieback, and foliage transparency) for trees alive in 1997*

Species	Mean slope	Probability	Number of plots	Number of trees
Crown Density:				
Shortleaf pine	-0.53	0.0681	60	249
Slash pine	1.35	0.0044	29	263
Loblolly pine	-1.43	0.0001	152	1,625
Virginia pine	-1.00	0.0096	43	424
Crown Dieback:				
Shortleaf pine	0.29	0.0904	60	249
Slash pine	-0.20	0.0005	29	263
Loblolly pine	0.20	0.0013	152	1,625
Virginia pine	0.86	0.0001	43	424
Foliage Transparency:				
Shortleaf pine	-0.32	0.1868	60	249
Slash pine	0.55	0.0737	29	263
Loblolly pine	0.81	0.0001	152	1,625
Virginia pine	0.38	0.3118	43	424

Table 2.—*Mean slope, probabilities, number of plots, and number of trees by pine species (shortleaf, loblolly, and Virginia) and crown variables (crown density, crown dieback, and foliage transparency) for trees that died after 1993*

Species	Mean slope	Probability	Number of plots	Number of trees
Crown Density:				
Shortleaf pine	-0.06	0.9661	12	17
Loblolly pine	-1.15	0.2784	29	41
Virginia pine	-1.73	0.0041	18	71
Crown Dieback:				
Shortleaf pine	-0.65	0.6107	12	17
Loblolly pine	1.51	0.1404	29	41
Virginia pine	2.54	0.0001	18	71
Foliage Transparency:				
Shortleaf pine	-0.15	0.8503	12	17
Loblolly pine	1.72	0.0809	29	41
Virginia pine	2.58	0.0869	18	71

needs to be recognized is that the initial mean values for each crown rating variable were more favorable in loblolly pine than in Virginia pine, so even a smaller change may be more critical for Virginia pine.

On the FHM plots, the relative number of sample trees from 1991 to 1995 is presented in figure 4. For slash pine, when ingrowth is factored into the total number, the relative number of trees in 1995 was 88 percent of 1991 numbers of trees and showed a major increase between 1994 and 1995. For loblolly, the number was 131 percent of the 1991 total. Both these results show that the mortality and cut trees are not being replaced in the sample population. The results for both Virginia and shortleaf pines show a steady decrease over time including the year (1995) when ingrowth was accounted for.

Another way to present these data is to examine the numbers of trees by 2-inch dbh class. Figure 5 shows a constant dbh distribution in loblolly pine for 1991, 1995, and 1997. But in Virginia pine, the distribution curve is shifting to a larger dbh class (fig. 6.). The 6-inch dbh class was most common in 1991 and 1995, but the 8-inch dbh class was the most common in 1997. This result also shows that for Virginia pine, the sample population is not being replaced for mortality and cut trees.

To determine if this decline in Virginia pine needs further attention, the FIA data set was examined. The analysis was conducted using the FIA interactive database retrieval system (located at web site - http://www.srs.fia.usfs.msstate.edu). Across the entire range of Virginia pine, mortality volume is 48 percent of the growth and removal volume is 92 percent of growth, for a net change of 140 percent—further evidence that Virginia pine that dies or is cut is not being replaced.

CONCLUSIONS

Based on the analysis of FHM crown density and crown dieback data, Virginia pine is showing a decline. In addition, loblolly pine is also showing a decline for these two crown variables and for foliage transparency. The FHM plot results for Virginia pines that died after 1993 identified larger annual changes (declines) than for trees that were still alive in 1997. The results from an examination of the number of sample trees and proportion of trees by dbh class show a sample population that is shifting from smaller trees to larger trees with very little recruitment in the smaller size classes. This relationship is the opposite of that found in loblolly pine. The implication is that the Virginia pine sample population is getting older and more susceptible to various stress-causing agents, especially ice damage and windthrow, which are common in older stands (Carter and Snow 1990).

The FIA data did show that mortality and removal volume was 140 percent of the growth, a net deficit. Because it is a relatively short-lived tree and intolerant of shade, Virginia pine will generally be replaced by more tolerant hardwood species (Carter and Snow 1990). So it appears this species is showing a decline based on both FHM crown rating information and FIA data for removals and growth, but that this is typical and expected due to the shade intolerance and short-lived nature of Virginia pine.

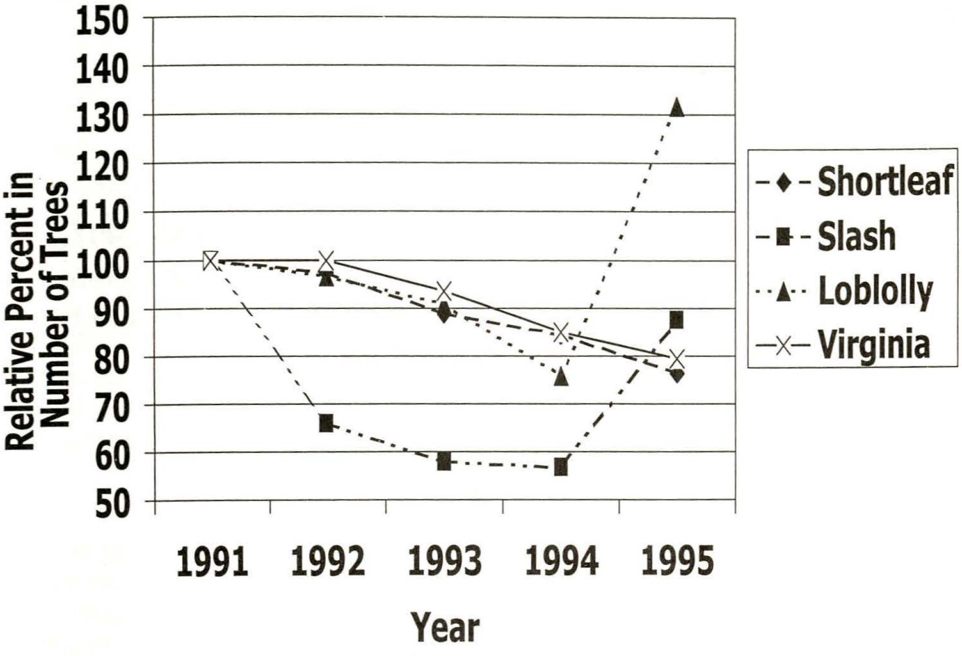


Figure 4.—*Relative change in numbers of live trees for shortleaf, slash, loblolly, and Virginia pines on FHM plots in Alabama, Delaware, Georgia, Maryland, New Jersey, and Virginia, 1991 through 1995.*

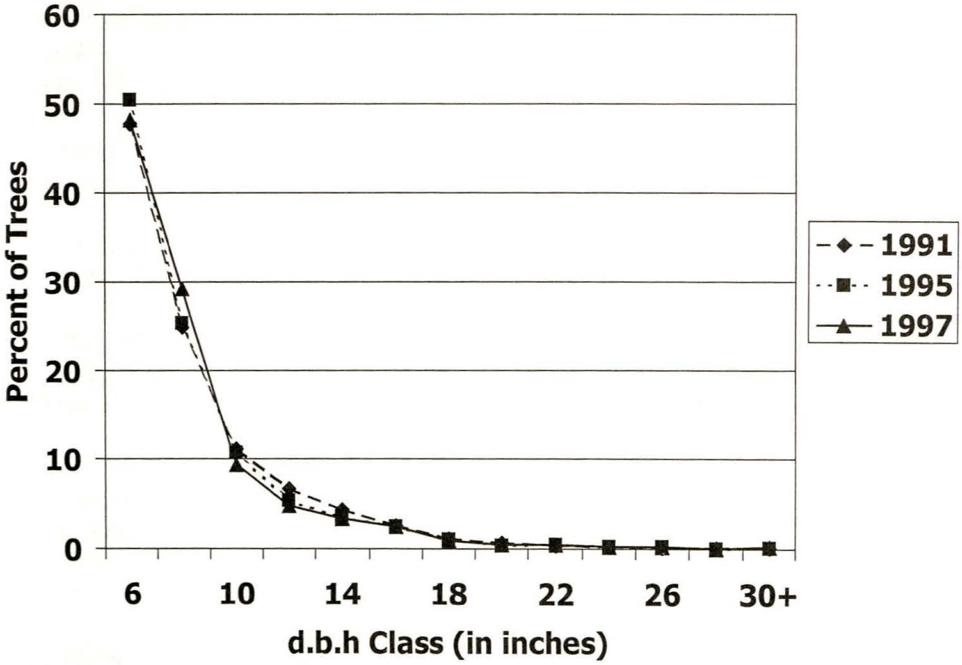


Figure 5.— *Distribution of live trees by 2-inch dbh class for loblolly pine on FHM plots in Alabama, Delaware, Georgia, Maryland, New Jersey, and Virginia, 1991 through 1995 and 1997.*

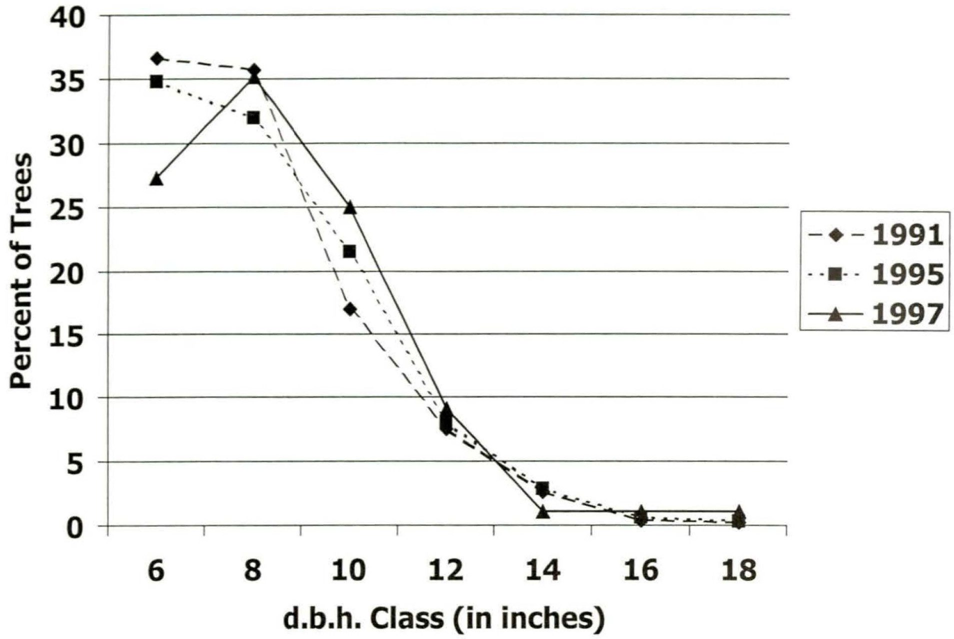


Figure 6.— *Distribution of live trees by 2-inch dbh class for Virginia pine on FHM plots in Alabama, Delaware, Georgia, Maryland, New Jersey, and Virginia, 1991 through 1995 and 1997.*

LITERATURE CITED

Anderson, R.L.; Belanager, R.P. 1987. A crown rating method for assessing tree vigor of loblolly and shortleaf pine. In: Phillips, D.R., comp. Proceedings of the 4th Biennial southern silvicultural research conference; 1986 November 4-6; Atlanta, GA. Gen. Tech. Rep. SE-42. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 538-543.

Burkman, W.G.; Vissage, J.S.; Hoffard, W.H.; Starkey, D.A.; Bechtold, W.A. 1998. Summary report: forest health monitoring in the South, 1993 and 1994. Resour. Bull. SRS-32. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 91 p.

Carter, K.K.; Snow, A.G., Jr. 1990. Virginia pine. In: Burns, R.M.; Honkala, B.H., tech. coords. Silvics of North America. Agric. Handb. 654. Washington, DC: U.S. Department of Agriculture, Forest Service: 1: 513-519.

Cox, S.; Schomaker, M.; Burkman, W.G.; Zarnoch, S.J.; Lackey, J. In prep. Crown condition guide: methods, training, and analysis techniques.

Eyre, F.H. 1980. Forest cover types of the United States and Canada. Washington, DC: Society of American Foresters. 148 p.

Millers, I.; Anderson, R.L.; Burkman, W.G.; Hoffard, W.H. 1992. Crown condition rating guide. Internal Rep. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Area State and Private Forestry, Forest Health Protection. 26 p.

SAS Institute Inc. 1989. SAS/STAT user's guide. vs. 6, 4th ed., vol. 1. Cary, NC: SAS Institute Inc. 943 p.

SAS Institute Inc. 1989. SAS/STAT user's guide. vs. 6, 4th ed., vol. 2. Cary, NC: SAS Institute Inc. 846 p.

Smith, W.D.; Gumpertz, M.L.; Catts, G.P. In review. Analyzing the precision of four sampling designs for change estimation in forest health monitoring. Forest Science.

Stolte, K.W. 1997. 1996 national technical report on forest health. Admin. Rep. FS-605. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 47 p.

USDA Forest Service. 1997. Forest health monitoring 1997 field methods guide. Internal Rep. Research Triangle Park, NC: U.S. Department of Agriculture, Forest Service, National Forest Health Monitoring Program. 128 p.

Forest Health Monitoring in California, Oregon, and Washington: Results and Interpretation

Richard T. Busing

Abstract.—From 1992 to 1997, standardized plots were established at about 500 sites in California, Oregon, and Washington as part of the national Forest Health Monitoring program. In California, 197 plots were established from 1992 to 1995; in Oregon and Washington, a total of 304 plots were established in 1997. Summarization of baseline data by state reveals similarities and differences among states. Trend analysis of the California data reveals few changes in forest structure variables, but substantial changes in certain crown indicator variables. For example, foliage transparency and crown dieback variables indicated improved crown condition since the 1992 drought. Additional trend data will allow further assessment of changes in tree condition in relation to environmental changes.

The detection monitoring component of the national Forest Health Monitoring Program includes plot data collection from a network of forested sites across the United States. Measurements of forest condition are made periodically at each site for monitoring and assessment of trends. California was the first Pacific Coast state in which Forest Health Monitoring plots were established. A grid of 197 forested sites was initiated there in 1992 and completed in 1995. Plots were established at most of the forested grid sites in Oregon and Washington in 1997. A comparison of baseline data among these Pacific Coast states is presented here. In addition, California data for certain indicator variables are examined for trends in forest condition from 1992 to 1996.

METHODS

Sampling Design

Sampling methods for Forest Health Monitoring are based on a rotating panel design with approximately 4,200 sites located on a triangular grid across the mainland U.S. (Palmer *et al.* 1991; fig. 1). In the western United States, data are collected every summer from one plot per site. Only a subset of sites is sampled each year; any given site is sampled at least once every 4 years. Baseline measurements are complete for sites in California, Oregon, and Washington. Eventually, sites in Alaska and Hawaii will be added to cover forest lands for all Pacific Coast states. I present baseline data from 1992 to 1995 in California and from 1997 in Oregon and Washington. I also present trend data from 1992 to 1996 in California.

Baseline Data

Using the Forest Health Monitoring grid (fig. 1), 197 sites were measured in California from 1992 to 1996. In 1997, 168 sites were measured in Oregon and 134 sites were measured in Washington. At each site, a cluster of four circular subplots totaling 0.067 ha in area was sampled. A combination of conventional stand mensuration techniques (e.g., stem density and basal area) and more recently developed indicators of health (e.g., sapling vigor, tree live crown ratio, crown dieback, and foliage transparency) were used within the plots. See Liegel and Busing (1996) for further information on the specific measurements applied in Pacific Coast states. Data were summarized by state in one of two ways depending on the parameter: (1) as a collection of site values averaged across all individuals in a plot, or (2) as a collection of tree values pooled across all trees in a region or state.

Trend Data

In California, the 52 permanent plots established in 1992 were revisited in 1996. During 1996, 10 additional plots on the grid network were measured. Thus, more sites were measured in 1996 than in 1992. Various forest health indicator measurements were made at each site (Liegel and Busing 1996). Of these variables, certain measures of tree crown condition were selected for trend analyses. Three crown condition variables (live crown ratio, crown dieback, and foliage transparency) showed high repeatability of estimation in comparisons between trainers and field crews in the Pacific Coast states. A cumulative distribution of site means for selected indicator variables was plotted for each sampling year, allowing comparison over time.

Research Ecologist, USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR 97331 USA.

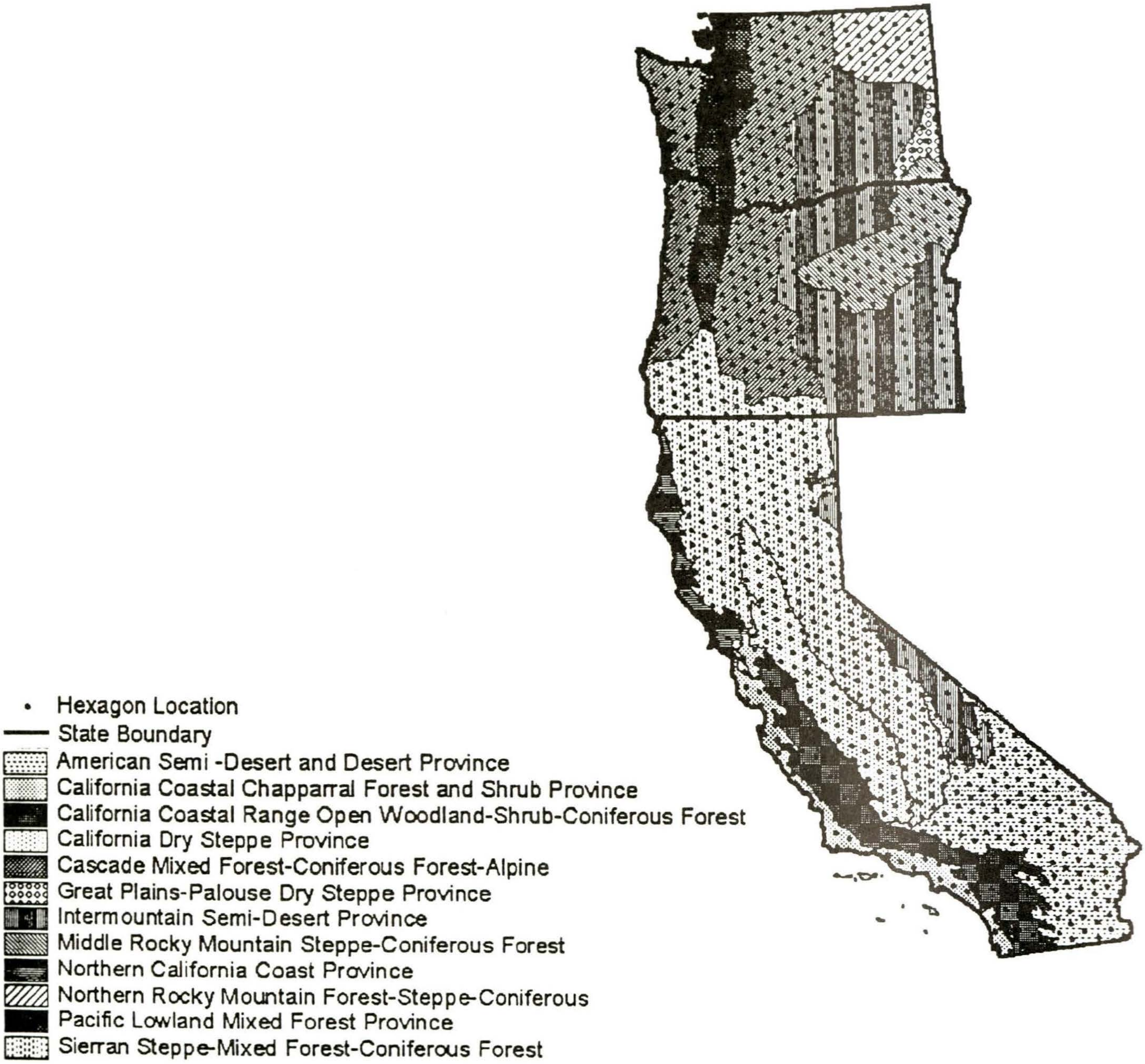

• Hexagon Location
— State Boundary
American Semi -Desert and Desert Province
California Coastal Chapparral Forest and Shrub Province
California Coastal Range Open Woodland-Shrub-Coniferous Forest
California Dry Steppe Province
Cascade Mixed Forest-Coniferous Forest-Alpine
Great Plains-Palouse Dry Steppe Province
Intermountain Semi-Desert Province
Middle Rocky Mountain Steppe-Coniferous Forest
Northern California Coast Province
Northern Rocky Mountain Forest-Steppe-Coniferous
Pacific Lowland Mixed Forest Province
Sierran Steppe-Mixed Forest-Coniferous Forest

Figure 1.—*The triangular grid of sites in California, Oregon, and Washington with Bailey's (1995) ecoregions.*

RESULTS

Baseline Data

The proportion of forested grid sites ranged from 31 percent in California to 51 percent in Washington (table 1). California and Oregon had a small percentage of woodland sites, and Washington had no woodland sites. Inaccessible forest sites made up less than 6 percent of the entire grid in each state.

The types of forests encountered differed strongly by state (table 1). For example, Douglas-Fir dominated about a third of the sites in Oregon and in Washington, but only 5 percent of the California sites. Sites with Hemlock-Spruce were common only in Washington. Hardwood-dominated sites were common only in California.

Stand structure showed several similarities among states (table 1). The mean densities of live seedlings and tree stems were similar among states. Mean live basal area values did not differ more than 6 m^2/ha among states.

Table 1.—*Forest attributes by state*

Attribute	California	Oregon	Washington
Land Cover (Percent of sites)			
Timberland	25	37	47
Woodland	3	5	0
Inaccessible forest	3	3	5
Non-forest	69	56	49
Forest Type (Percent of forested sites)			
Douglas-Fir	5	31	39
Pine	16	21	14
Fir-Spruce	14	4	7
Hemlock-Spruce	1	5	25
Redwood	1	0	0
Mixed Conifer	17	21	11
Hardwoods	30	5	2
Other	16	13	2
Stand Structure (Mean and standard deviation)			
Seedling density (n/ha)	1,914±349	1,905±305	2,073±381
Stem density	913±27	887±76	956±148
Snag density	25±3	32±4	59±7
Basal area (m^2/ha)	27±2	27±2	33±2
Tree Species Diversity (Mean and standard deviation)			
Species richness	2.9±0.1	3.0±0.1	3.0±0.1
Simpson diversity	0.29±0.02	0.32±0.02	0.32±0.02
Shannon diversity	0.47±0.03	0.52±0.03	0.55±0.03

However, snag density was noticeably high in Washington. Live tree diameter distributions for each state were log-linear in form (fig. 2). Similarity in the percent frequency of stems in each size class was evident.

Mean tree species diversity of sites did not differ strongly among states (table 1). Species richness (species counts) means ranged from 2.9 in California to 3.0 in Oregon and Washington. Although mean species richness values were quite similar among states, richness as well as the Simpson and Shannon diversity indices were lowest in California.

Baseline values for certain forest health indicator variables differed by state. In Washington, for example, good sapling crown vigor ratings were infrequent and average ratings were frequent in comparison to California and Oregon (fig. 3). In California, mean foliage transparency of tree crowns was relatively low (fig. 4).

Several forest health indicator variables were similar across states. Distributions of mean live crown ratio differed only slightly among states (fig. 5). The same was true for mean crown dieback (fig. 6). The frequency of trees lacking damage was also similar among states (fig. 7).

Trend Data

Distributions of mean live crown ratio in California were similar between 1992 and 1996 (fig. 8a), suggesting little change in live crown ratio across the State. However, distributions of mean crown dieback (fig. 8b) and foliage transparency (fig. 8c) suggested poorer crown condition in 1992 than in 1996.

DISCUSSION

Several similarities in baseline data are evident among the three states studied. Mean tree species diversity, quantified by richness, does not differ greatly among states.

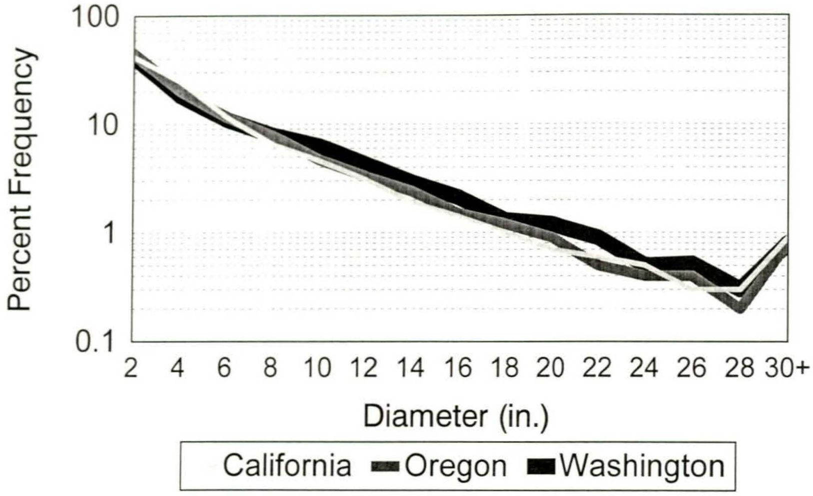


Figure 2.—*Diameter distributions of live trees by state.*

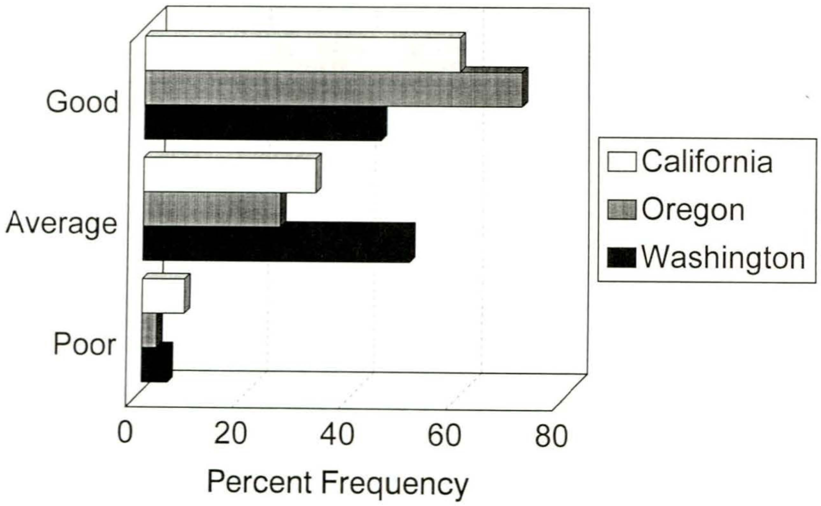


Figure 3.—*Sapling crown vigor ratings by state.*

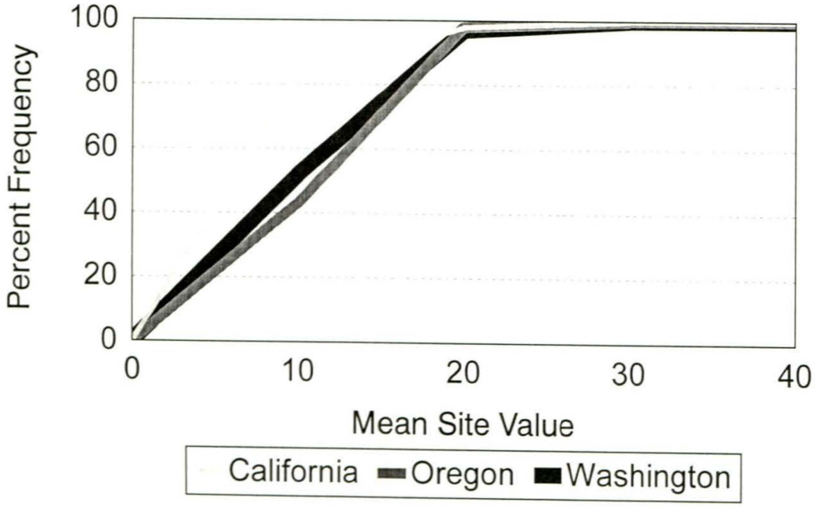


Figure 4.—*Cumulative distributions of foliage transparency by state.*

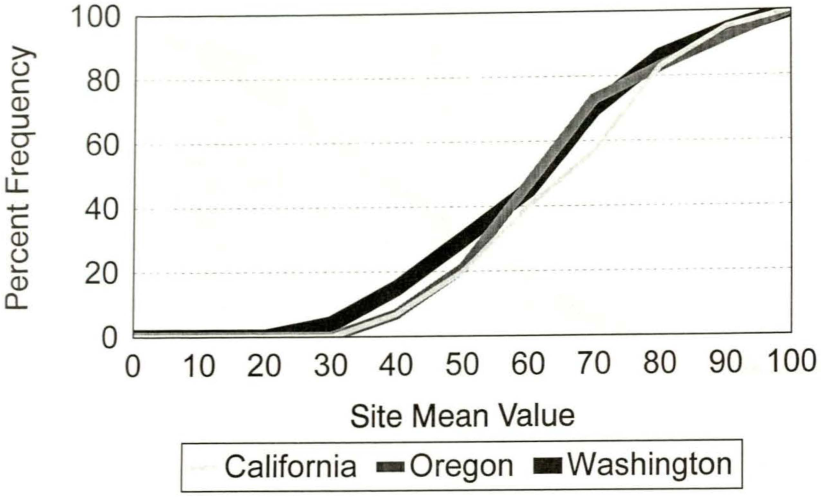


Figure 5.—*Cumulative distributions of live crown ratio by state.*

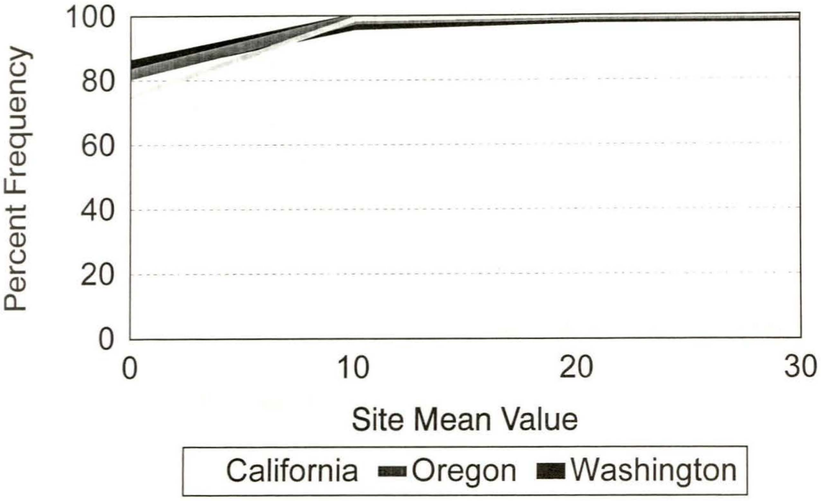


Figure 6.—*Cumulative distributions of crown dieback by state.*

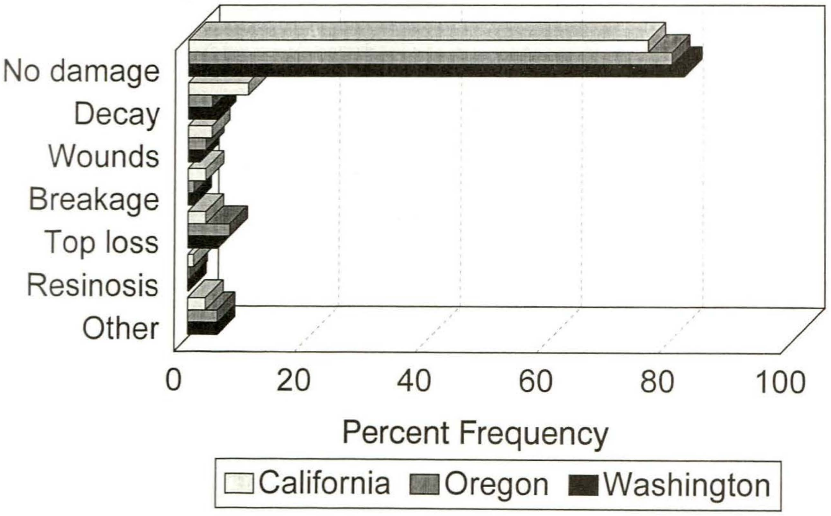


Figure 7.—*Tree damage by state.*

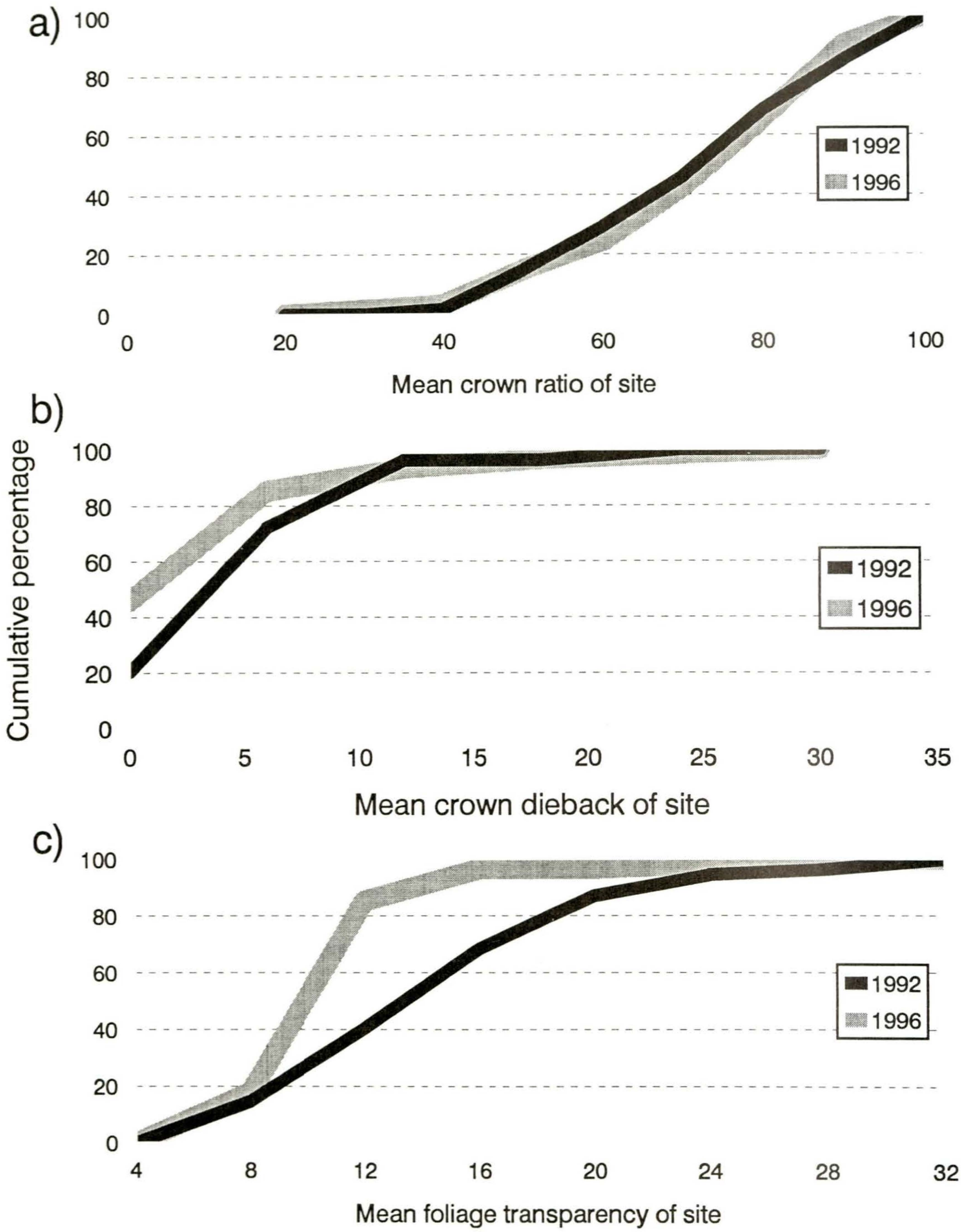


Figure 8.—*Cumulative distributions of indicator variables in California for 1992 and 1996: (a) live crown ratio, (b) foliage transparency, and (c) crown dieback.*

Although tree species composition differs among states, the mean number of tree species encountered per site is similar. In addition, total stand density and basal area of live stems do not differ greatly among states. Tree diameter distributions are log-linear in form and similar among states. The log-linear diameter distribution, common in uneven-size forest stands (Leak 1965), also occurs across these large regions that have a mixture of stands with contrasting structures and disturbance histories. Of the forest health indicators examined, distributions of site mean live crown ratio and site mean crown dieback are similar among states. In each state, approximately 20 percent of live trees had at least one type of damage recorded.

There are several notable differences in baseline data among the three states. For obvious biogeographic reasons, the proportion of forested land and the species composition of forests differed among states. The reasons for other differences such as the high snag density in Washington are less clear and require examination of other data or further study. Differences in forest health indicators among states require careful examination. Of the indicators examined here, sapling crown vigor and foliage transparencies showed differences among states. The reasons for these differences must be studied for effective long-term monitoring and assessment. It is critical that the sources of these differences are elucidated. Whether they are the result of human error, or biological or environmental differences has bearing on their interpretation.

The observed changes in crown dieback and foliage transparency from 1992 to 1996 in California indicate improved crown condition of live trees over the period. This improvement is correlated with increased rainfall since late 1992, the end of a multiple-year drought. Thus, these indicators may respond to drought stress. Their ability to detect effects of droughts and other environmental stresses can be assessed as further trend data become available.

ACKNOWLEDGMENTS

Thanks are extended to Sam Solano, Carolina Hooper, and the West Coast field personnel. A computer program written by Bill Bechtold and Stan Zarnoch was useful in summarizing the data. The following people reviewed this manuscript: Barbara Conkling, Forestry Sciences Laboratory, Research Triangle Park, NC, USA; Steve Acker, Oregon State University, Corvallis, OR, USA.

LITERATURE CITED

Bailey, R.G. 1995. Description of the ecoregions of the United States. Misc. Publ. 1391. Washington, DC: U.S. Department of Agriculture.

Leak, W.B. 1965. The J-shaped probability distribution. Forest Science. 11: 405-419.

Liegel, L.H.; Busing, R.T. 1996. Forest health detection monitoring results, 1992-1995. In: California forest health in 1994 and 1995. Rep. R5-FPM-PR-002. San Francisco, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region. 63 p.

Palmer, C.J.; Ritters, K.H.; Strickland, T.; Cassell, D.L.; Byers, G.E.; Papp, M.L.; Liff, C.I. 1991. Monitoring and research strategy for forests-environmental monitoring and assessment program. EPA/600/4-91/012. Washington, DC: U.S. Environmental Protection Agency.

FIA Forest Inventory Data for Wildlife Habitat Assessment

David C. Chojnacky

Abstract.—The Forest Inventory and Analysis (FIA) program of the USDA Forest Service maintains a network of permanent plots to monitor changing forest conditions. These plots were originally established to monitor the nation's timber supply; however, these data have great potential for evaluating other forest resources. To demonstrate a wildlife application, an assessment of Mexican spotted owl habitat was done with FIA data from the Gila National Forest, New Mexico.

The Forest Inventory and Analysis (FIA) program in the Interior West monitors forested plots in a 3-mile grid for all land ownerships in Idaho, Montana, Nevada, Utah, Wyoming, Colorado, New Mexico, and Arizona. A *double sampling for stratification* design (Chojnacky 1998) is used to combine the ground plots with a more intensive data grid from aerial-photo plots to produce resource statistics. Plot locations in both phases sample about an acre. Individual trees are measured on ground plots with a subplot design.

Historically, FIA data have been used to compile tables of statewide statistics primarily describing tree attributes such as volume, growth, and mortality for numerous land ownership and classification categories (Conner *et al.* 1990, Van Hooser *et al.* 1993). The FIA summary tables and accompanying database (Woudenberg and Farrenkopf 1995), although useful for many timber applications, have had limited use for assessing wildlife habitat. However, there is great opportunity to use FIA tree attribute data—the backbone and strength of the FIA program—to develop new analyses and indices tailored to specific wildlife needs. The challenge is establishing clear linkages between the FIA tree data and structural habitat arrangements used by wildlife.

In this paper, stand density measures are used to link FIA tree data to Mexican spotted owl (*Strix occidentalis lucida*) habitat on the Gila National Forest in New Mexico. Information on habitat for Mexican spotted owl has been in high demand since the U.S. Department of the Interior Fish and Wildlife Service listed the owl as *threatened* in 1993 (under authority of the Endangered Species Act of 1973 and amendments) (USDI 1995).

METHODS

The FIA data for this study were gathered from the 3.3-million acre Gila National Forest, which was inventoried in 1993 to 1994 by private contract using standard FIA field procedures in a *double sampling design* (USDA 1993). First-phase stratification included sampling about 13,500 map and aerial-photo points in a 1-km grid. In the second phase, 464 permanent field plots were established in a 5-km grid (fig. 1).

Two stand-density measures, q-factor (Meyer 1952) and SDI (Long 1998), were calculated from the FIA tree data:

$$q = \exp(-2*\text{slope}) \quad (1)$$

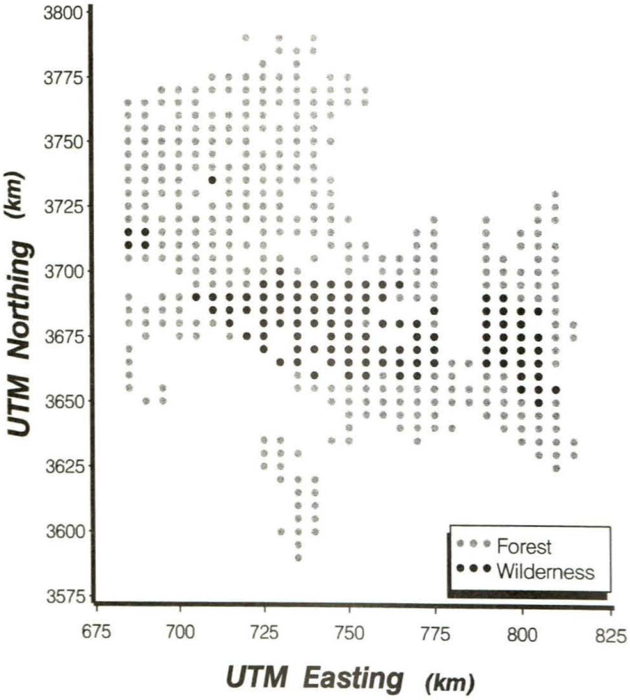


Figure 1.—*Map of 464 FIA plots established in 1993 and 1994 on the Gila National Forest in a 3.1-mile (5-km) grid for both managed forest and wilderness. UTM Easting is standardized to one grid zone for mapping.*

Research Forester, USDA Forest Service, Rocky Mountain Research Station, Logan, UT USA (also adjunct faculty, Forest Resources Department, Utah State University).

where

q = density factor calculated for each plot from trees per acres (TPA) within 2-inch diameter classes ($DCL\ 2$)

$slope$ = slope (b) of linear regression for each plot: $1nTPA = a + b\ DCL\ 2$

$$SDI = \Sigma\ (DBH_i/10)^{1.6} \tag{2}$$

where

SDI = stamd density index calculated for each tree and summed, much like individual tree diameters are used to calculate plot basal area

dbh = diameter at breast height of the i*th* tree in a plot or stand

The q-factor and SDI were computed for each FIA plot.

SDI was expressed as percent of its maximum by using Southwestern Region Forest Service standards (for maximum SDI) applied to FIA defined forest types. The maximum SDI's used for the various forest types were: 420 for cottonwood, 450 for ponderosa pine, 595 for Douglas-fir, 830 for white fir, and 670 for spruce/fir.

SDI was also used to characterize stand structure within five diameter classes using classes defined the same as vegetation structure stages (VSS), which have been used in the Southwest (Reynolds *et al.* 1992, p. 2). The five diameter classes were used to calculate a *stand density diameter class index* (SDDI) by regressing percent SDI in a diameter class against diameter class (Chojnacky and Dick [In preparation]). This index (the regression intercept) rated plots according to how balanced SDI was among diameter classes. For example, an SDDI near 20 percent corresponded to a balanced or equal distribution of SDI among all five diameter classes. An SDDI below 20 percent meant *less* SDI in smaller diameter classes than in larger classes, and above 20 percent meant *more* SDI in smaller diameter classes than in larger classes. Therefore, an SDDI between 10 and 30 percent generally represented some SDI in all diameter classes.

The density data were classified for cover type according to Mexican spotted owl Recovery Plan guidelines (USDI 1995). Three classes corresponding to owl habitat were identified. The average species mixtures for each class were:

1 **Ponderosa pine**—62 percent *Pinus ponderosa*, 16 percent *Juniperus deppeana*, 8 percent *Quercus arizonica*, 6 percent *P. edulis*, and 5 percent *Q. gambelii*

2 **Pine-oak**—47 percent *P. ponderosa*, 33 percent *Q. gambelii*, 9 percent *J. deppeana*, and 7 percent *P. edulis*

3 **Mixed conifer**—34 percent *P. ponderosa*, 25 percent *Psuedotsuga menziesii*, 9 percent *Abies concolor*, and 5 percent *P. strobiformus*.

These three cover classes included 213 plots representing 1.4 million acres, less than half of the Gila National Forest.

RESULTS AND DISCUSSION

The density measures were graphed against each other to determine a range of possible habitat conditions suitable for owls. For example, SDDI less than 30 percent and percent of maximum SDI between 25 and 60 percent represented moderately dense plots that have balanced all-size tree distributions or more large than small trees (fig. 2). This range does not necessarily define true Mexican spotted owl habitat conditions, but it is a reasonable range for illustrating possible summary results with FIA data.

Given the hypothetical density range for owl habitat (fig. 2), area summary showed confidence intervals ranging from 20 to 35 percent for mixed conifer and ponderosa cover classes (fig. 3). These confidence intervals are probably too large to effectively monitor owl habitat for a single national forest, but regional estimates based on FIA data for several national forests are likely to narrow confidence intervals to more acceptable ranges.

Owl habitat was about evenly distributed between the Gila's wilderness and managed forest (fig. 3). FIA data contain many other classification variables that could be used to draw inferences about management implications from forest conditions or land use.

In summary, the FIA data show promise for monitoring Mexican spotted owl habitat at a regional scale. However, a critical linkage between owl habitat requirements and FIA tree density measures (functions of SDI or q-factor) is lacking. Owl demographics need to be compared to FIA data to determine appropriate ranges for suitable habitat. Nevertheless, the FIA network of plots is a ready source of information that could describe and monitor the owl's habitat needs.

ACKNOWLEDGMENTS

I wish to thank the reviewers of this manuscript: Sharon Woudenberg of Forest Inventory and Analysis at the USDA Forest Service, Rocky Mountain Research Station, Ogden, UT, USA, and Jim Dick of the USDA Forest Service, Southwestern Region, Albuquerque, NM, USA.

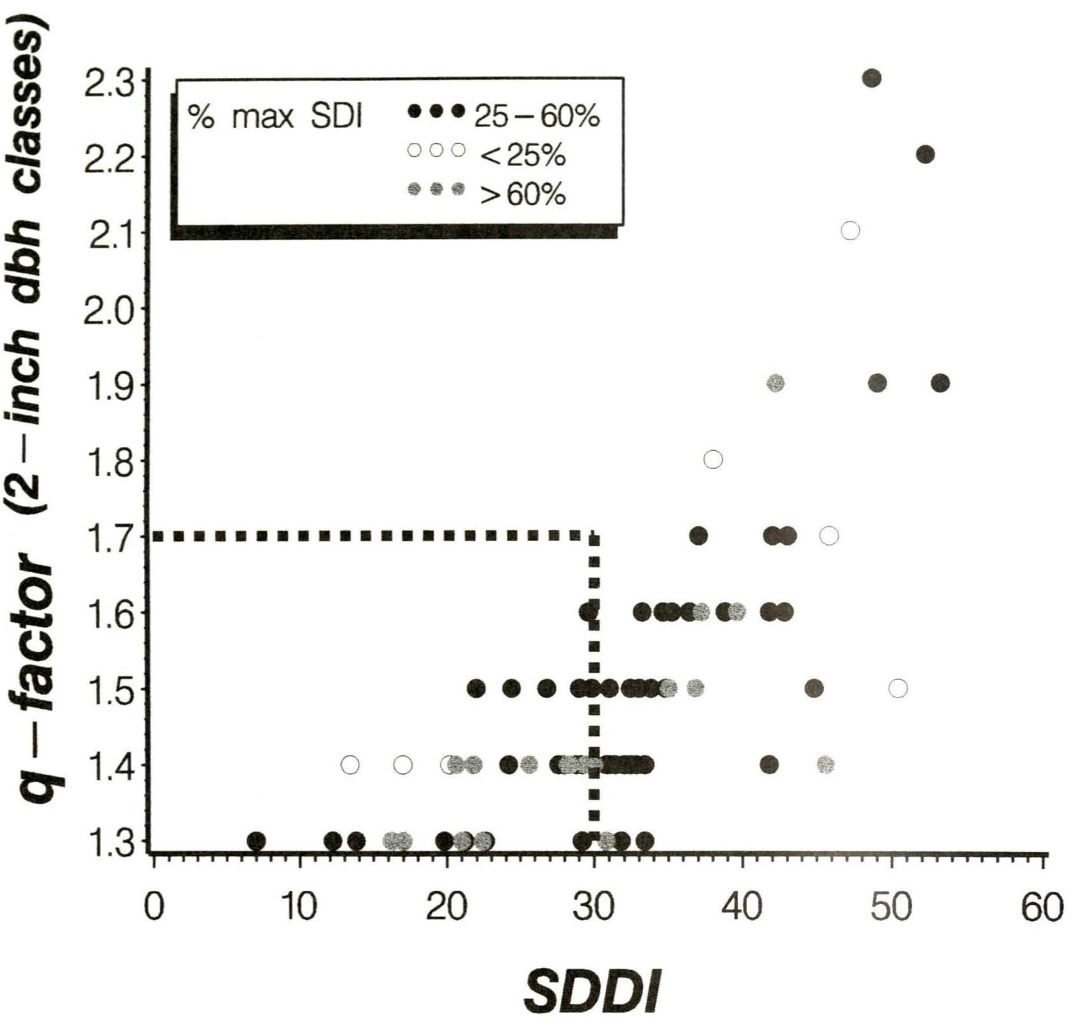
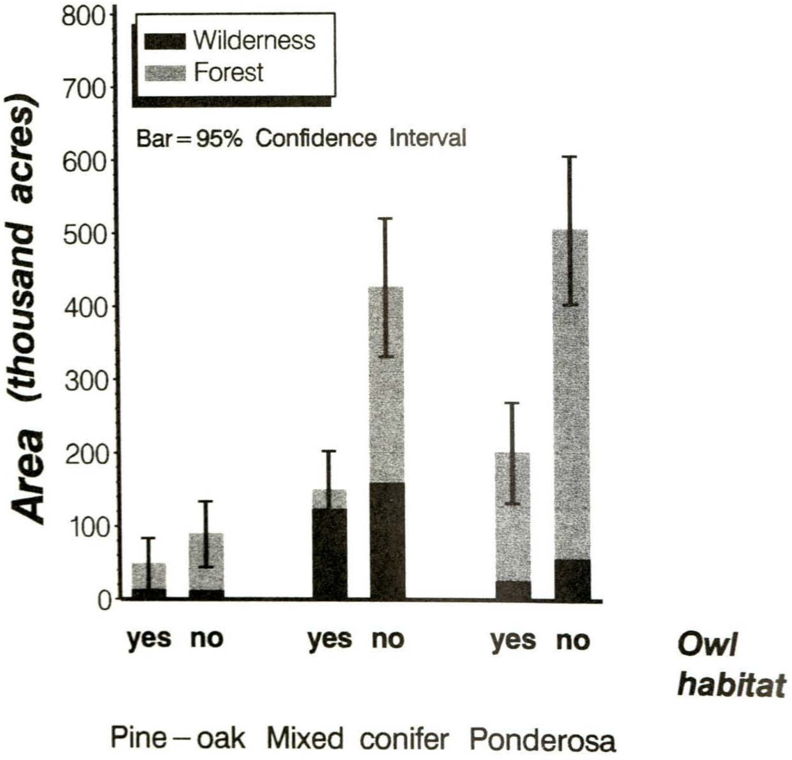


Figure 2.—*Comparison of three ways to measure density for the mixed conifer cover class in the Gila National Forest. More favorable stand density for Mexican spotted owl is highlighted within the dashed box.*

Figure 3.—*Example of Mexican spotted owl habitat where stand density conditions are selected for SDDI less than 30, and percent of maximum SDI between 25 and 60 percent, 1993-94 Gila National Forest inventory.*



LITERATURE CITED

Chojnacky, D.C. 1998. Double sampling for stratification: a forest inventory application in the Interior West. Res. Pap. RMRS-RP-7. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 15 p.

Chojnacky, D.C.; Dick, J.L. [In preparation] Habitat assessment for Mexican spotted owl using FIA forest inventory data. Logan, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Forestry Sciences Laboratory.

Conner, R.C.; Green. A.W.; Born, J.D.; O'Brien, R.A. 1990. Forest resources of Arizona. Resour. Bull. INT-64. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 92 p.

Long, J.L. 1998. Multiaged systems in the Central and Southern Rockies. Journal of Forestry. 96(7): 34-36.

Meyer, H.A. 1952. Structure, growth, and drain of balanced uneven-aged forests. Journal of Forestry. 50(2): 85-92.

Reynolds, R.T.; Graham, R.T.; Reiser, M.H.; *et al.* 1992. Management recommendations for the northern goshawk in the Southwestern United States. Gen. Tech. Rep. RM-217. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 90 p.

U.S. Department of Agriculture, Forest Service, 1993. Interior West forest land resource inventory field procedures. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station, Forest Survey. 180 p.

U.S. Department of the Interior, Fish and Wildlife Service. 1995. Recovery plan for the Mexican spotted owl: Volume I. Albuquerque, NM: U.S. Department of Interior, Fish and Wildlife Service. 172 p.

Van Hooser, D.D.; O'Brien, R.A.; Collins, D.C. 1993. New Mexico's forest resources. Resour. Bull. INT-79. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 110 p.

Woudenberg, S.W.; Farrenkopf, T.O. 1995. The Westwide forest inventory data base: user's manual. Gen. Tech. Rep. INT-317. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 67 p.

The Forest as a Warehouse

C.J. Goulding

Abstract.—New Zealand's timber harvest is rapidly increasing and will continue to do so over the next 20 years. This increase provides opportunities for adding value and increasing profitability, but to achieve the full potential of the harvest, the best management decisions at strategic, tactical, and operational levels are required. The key to *market-driven harvest planning* in New Zealand is a greatly improved knowledge of the quantity, quality, and condition of the standing trees. Industry is demanding that pre-harvest inventory be intensified with more detail about the quality of the stems, more geographical precision as to the location of the potential log products, and more flexibility in the analysis of the data. Improvements in instruments for use in the forest, in remote sensing techniques, and in operations research and geostatistical algorithms should lead to better computer-based decision support systems.

New Zealand has 1.7 million ha of plantations, expanding at a rate of 75,000 ha per year, averaged over the last 5 years. The main tree species is radiata pine, which is intensively managed for wood production and for profit. Last year's harvest was 16 million m^3, and production is forecast to rise to 30 million m^3 by 2010. Much of this production is exported, so the needs of the international market determine marketing and harvest planning. Timely silviculture, involving heavy thinning and pruning of live green branches, produces logs with a high proportion of uniform-grained clearwood. However, fast growth with a tendency for large branches and stem malformation also produces chip-logs, where the low value is determined by poor quality, not necessarily by small end diameter alone. The differential in value between the highest and lowest value logs is wide, by a factor of 6 to 10 or more.

Marketing and facility planning require information well in advance of the start of harvesting. A 3- to 5-year forecast of production is required, prepared in conjunction with marketing exercises or new facilities and product-line planning. Here, marketing is defined as determining what products potential customers require that the organization can supply, as opposed to sales, which is defined as finalizing an agreement to supply a given product.

In the past, there was a lengthy delay between when a decision was made to fell a block of trees and when the timber, panel, or paper products were delivered to the final customer. The timing of the decision was mainly production driven, derived from the long-term yield regulation and management plan, modified by operational logging schedules. The sale of the end product following sawmilling, peeling, or pulping was made with only limited ability to take the short-term needs of the market into account.

Current mechanized harvesting, high-speed processing facilities, and short drying or pulping schedules can shorten the time between deciding to harvest and producing the end-product ready for delivery to less than a week. Logging and processing operations can be *just in time*, where trees of the appropriate quality are felled only when required to fill a sales order for an end product. Within the constraints imposed by longer term plans, short-term logging planning now has the potential to become truly *market driven*.

Both intermediate and short-term *market-driven* plans will require estimates of total standing and recoverable log-product volumes for each potential coupe, rather than broader based estimates at the stand or age-class level. They will also require calculations to be made of the marginal rate of return obtained by leaving a coupe to grow a further year, either explicitly or implicitly within a short-term mathematical programming system.

The area of a New Zealand stand can be large, covering several coupes. Even though it contains one even-aged species, variability across a stand can be high. The trend is for coupes to become smaller, and a harvest plan will comprise many such coupes, each requiring accurate inventory, in detail and to a strict level of precision. Using only ground-based inventory techniques will require very high proportions of the trees to be measured and are too expensive to be carried out at this intensity except on a cursory, quickly executed basis. Logging planning is forced to place great reliance on past experience, theoretical models, and ocular estimates. Currently, the best estimate for the next week's production in a

---

Scientist, New Zealand Forest Research Institute Limited, Sala Street, Private Bag 3020, Rotorua, New Zealand.

coupe is what was produced last week. The results from such assessments are not ideal for quantitative, computer-based planning in a rapidly changing environment.

If inventory can be improved so that the flexibility of the trees to yield differing volumes of logs in response to changing relative values and specifications is known, the forest can be considered as a *warehouse* of potential log products. It is essential that the whereabouts of those trees able to produce logs of the required type are precisely known. This also implies more intensive assessment of the stem to more precisely determine the quality characteristics required by each potential log type.

To achieve this requires research to improve:

- software systems for pre-harvest inventory
- the intensity of measurement on the standing tree of external features of stem quality, such as branches and stem sweep and of intrinsic wood quality, and the way size and quality can be projected into the future
- the spatial resolution of inventory, so that results at an acceptable level of sampling precision can be geographically interpolated across the stand's area
- methods to keep track of trees and logs during harvest, and to forecast what can be harvested during the next few weeks

PRE-HARVEST INVENTORY

The standard pre-harvest inventory method used by New Zealand and Australian forestry companies is the Method of the Assessment of Recoverable Volume by Log-types, MARVL (Deadman and Goulding 1979, Goulding *et al.* 1993). A key feature of the system is that it recognizes that merchantable yields depend on the types of log products to be harvested and on their relative values. When these change, the volumes of the various products harvested will change (see Puumalainen 1998). Field assessment uses simple-, stratified-random, or double sampling with bounded or Bitterlich plots. It measures a sample of trees and objectively assesses quality changes up the stem independently of log specifications. Computer analysis models the breakage, volume, taper and grades of the tree stems based on the field data, and then predicts the yield of log products by mimicking bucking. Dynamic programming is used to calculate the bucking pattern so that the total value of the logs obtained is maximized for each stem. A list of log products and their specifications, including their relative values, is supplied by the user at the time of each analysis, and the inventory data can be reanalyzed many times with different sets of specifications. Varying the log-product specifications and reanalyzing the data allows marketing or planning personnel to determine the sensitivity of the yields to changes in those specifications. Growth routines can project the inventory data forward a few years, and the results can be reanalyzed to assess the change in the volumes of the various products. When a stand is marginal with respect to meeting the minimum size requirements of valuable logs, rescheduling the date of logging could give extra growth and allow the minimum size to be achieved, with an increase in value greatly in excess of the volume increment.

The latest version of the MARVL system is implemented under MS Windows™, closely integrating the analysis modules with growth prediction and with a database capable of linking to a GIS (Gordon *et al.* 1995). A major upgrade is being carried out now. The most visible new features are improved user friendliness; the ability to cater for mixed species, as found in tropical forests for example; and an increase in the level of detail that a stem can be assessed for quality. The redesign should more easily allow inventory modules to be incorporated into systems that optimize log allocation to customers (Cossens 1996).

INTENSITY OF MEASUREMENT

Because stem quality is assessed visually in the MARVL field procedure, there is a limit to the accuracy with which characteristics such as branch size can be estimated. The effect of stem sweep on potential log-product yield is difficult to judge accurately. Although the analysis procedures allow changes in log specifications, results can only be predicted if the requisite qualities are assessed first in the field. A supplementary method was required that could take precise measurements on trees without felling or climbing, and could allow re-calculation or re-measurement some time after the first analyses were carried out.

A research program funded by the New Zealand forest industry began in 1994 to develop a new measurement procedure with the desired accuracy. The method uses terrestrial photogrammetry to provide mensuration data from images of a sample of standing trees. Initial tests have shown that under operational conditions it should be possible to routinely measure the heights of branch clusters and other stem features to within ±0.1 m and upper stem diameters to within ±10 mm. Errors in measuring branch diameters range from an underestimate of 2 mm to an overestimate of +7 mm. The method also provides a permanent photographic record that enables measurements to be checked or reworked.

Work is being carried out to determine optimal double sampling systems, where the large sample of trees is either measured only for dbh, or receives the regular ocular estimate of stem qualities. Alternatively, multiphase sampling may be employed, using the results of the photogrammetric measurements to stratify stands or to develop regression models.

SPATIAL DISTRIBUTION

In New Zealand plantations, trees are planted in rows laid out fairly precisely, and the tree planters are able to correctly space the trees within the rows to achieve the prescribed number per hectare. Even so, the trees are not in a perfect matrix, and rows waver around natural obstacles. With unthinned stands, mortality due to competition can be severe after age 20. Many stands are thinned at least once, either "thinning to waste," where the trees are not extracted, or "production thinned," where access rows are removed and selective thinning occurs in between. Especially with machine thinning, clumps of trees can be missed, or trees felled to leave gaps for equipment maneuverability. The number of stems at rotation time is often less than one quarter of the number planted. This, combined with site differences, causes spatial variability between and within what appear to be uniform stands.

The results provided from the MARVL inventory method have been sufficiently accurate and useful for the amount of pre-harvest inventory in New Zealand to have greatly increased over the past decade. To estimate population totals within the confidence intervals desired by management requires 20 to 50 or more plots, involving 2 or more days' work for a single field crew. Reducing the area of a population does not necessarily greatly reduce plot variability, and providing estimates for smaller and smaller size areas is limited by the amount and cost of the additional field work required. Precise information is not available for areas with much fewer than 12 to 15 plots. To mitigate this problem and to provide the increased spatial information required, three approaches are being considered.

The first uses geostatistical procedures, such as kriging, to interpolate between values measured on plots with known locations. Hock *et al.* (1993) used kriging to provide estimates of site index across the 160,000-ha Kaingaroa forest, interpolating between estimates provided by permanent sample plots, combined with other available information. Gunnarson *et al.* (1998) describe the potential of kriging to assist in Scandinavian forestry, including the estimation of total standing volume, and its subdivision by species classes. A difficulty with New Zealand inventory plots is the high between-plot variance, due to the traditional relatively small size of the plots. These are usually less than 0.06 ha in area, or have a basal area factor that counts 8 to 10 trees per point. The variability is very noticeable when predicting "rare" products, which may not be present in every tree, but which are valuable none the less. An attempt to predict a 3-D surface model of the geographical distribution of volume in a stand by using non-statistical, numerical analysis techniques failed because of this reason, despite there being as many as 58 closely spaced inventory plots.

Of the two alternative methods under research, one combines satellite imagery with stand maps and inventory plots in a multisource inventory procedure and the other uses automatic image processing of large-scale aerial photography to identify the location of each individual tree.

Multisource Satellite Inventory

Satellite imagery has been available for more than 20 years, producing spectacular photos and promising detailed forest management information. This promise has not materialized under New Zealand's exotic forest conditions, nor, apparently, elsewhere (Holmgren and Thuresson 1998). However, recent collaborative work with the Finnish Forest Research Institute and with Landcare Research NZ has shown that combining satellite imagery with estimates from inventory ground plots can produce estimates of product volumes geographically distributed within stands. This "multisource" inventory method is used in the Finnish National Forest Inventory (Tomppo 1996) where it is increasingly a source of management and operational planning data. Many ground plots are inventoried, the data from which are combined with data from other sources—stand maps and Landsat TM satellite imagery, or its equivalent. For each 25-m square in the forest depicted by a pixel on the satellite image, the forest parameters of interest are estimated using a nearest neighbor estimation method combining the data from six wavebands of the image with the data from the field plots. A GIS can be used to display maps of species composition, volumes of growing stock, biomass, or other parameters. Each estimate for a 25-m square is very imprecise, but when the individual values within a defined area are averaged, estimates specific to localities smaller than those of the original inventory populations are produced.

Our initial research was to determine if the system could be applied to New Zealand radiata pine with the estimates of log-product volumes derived from MARVL. If so, then the method could predict log-product volumes for small coupes and define within-stand variability. A trial forest block of 1,000 ha consisted of radiata pine ranging from new planting through to mature 28-year-old stands. The former Forestry Corporation of NZ supplied data from 188 of their inventory plots in the block. A Landsat TM image taken in December 1990 was also available. For selected stands within the block, estimates were made of the total standing volume and the volumes of pruned logs, saw logs, and pulp wood for each 25-m square (Tomppo *et al.* 1996). Figure 1 depicts a raster map of estimates of total standing volume across two compartments in the forest.

The research confirmed that the method is sound over larger areas in New Zealand plantations. However, it also showed that for even-aged stands of 40 ha or less, volume estimates were biased; that is, volumes on stands with low volumes per hectare were overpredicted, while those with high values were underpredicted. Further work (Trotter *et al.* 1997) showed that it is possible to produce unbiased estimates at the stand level by estimating the coefficients of linear regressions with volume as the independent variable and Landsat TM band 4 the dependent variable, then inverting the equation. The estimates for very small areas still have wide confidence limits, but even at this level of imprecision, the methods give useful additional information on the spatial distribution of volume. Areas of damage are clearly visible, as are patches of higher and lower volumes that cannot be determined from plot data alone.

Automatic Delineation of Individual Trees

An alternative method of determining the spatial distribution of product volumes is to automatically identify the location of each individual tree within a stand or coupe, stratify if necessary, count the trees, and combine the count with measurements from an individual tree sample. For small woodlots, area estimates may be poor due to indistinct boundaries; a good way of providing an owner with volume estimates for the whole woodlot is to multiply average tree parameters by the total number of trees present.

It is sufficient if the tree location is determined to within several meters or so, and the problem reduces to one of correctly identifying a single tree apart from its neighbors. When the locations of trees are entered into a GIS, it will be possible to accurately count the number of trees in any coupe or subdivision of a stand, or to subdivide areas into

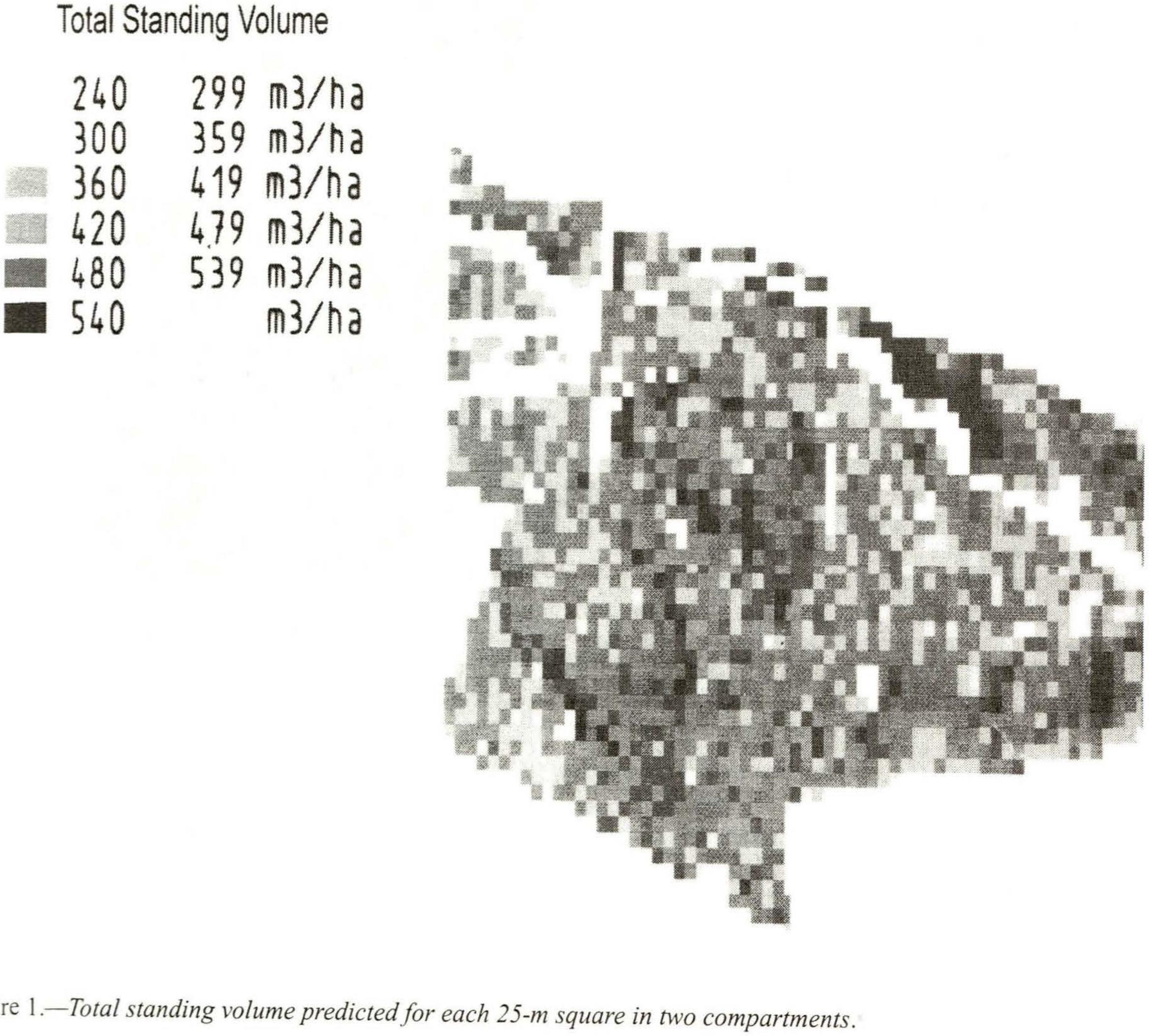


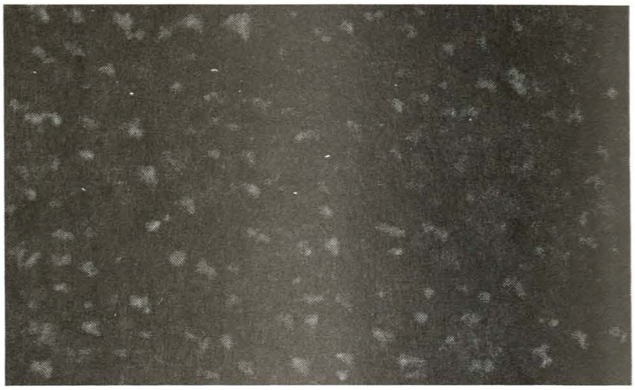
Figure 1.—*Total standing volume predicted for each 25-m square in two compartments.*

more uniform blocks. Given an accurate count, and the additional knowledge of the spatial distribution of the stems, it should be possible to use individual tree sampling techniques to indicate the spatial distribution of log products.

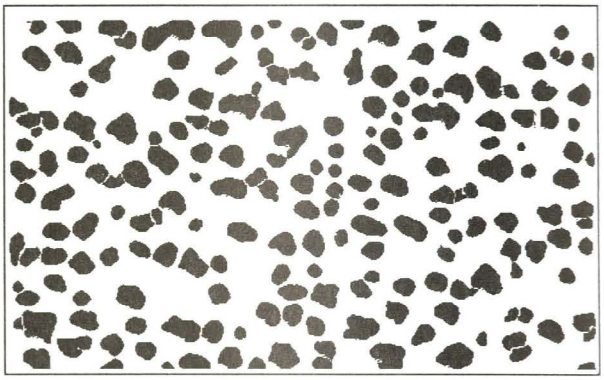
In the last 6 or so years, methods of automatically delineating tree crowns from aerial photography have been reported in the literature. Large-scale photographs are scanned, and the reflectance values of each sub-meter pixel analyzed. For example, on planted Norway spruce in Denmark, Dralle and Rudemo (1996) carried out a method of kernel smoothing and then counting maxima above a threshold level. They reported being able to locate trees in stockings ranging from 367 to 1,257 per hectare in a thinning experiment, with tree count errors of less than 7 percent. We recently tested the method described by Gougeon (1995, 1997). This method is described as a "valley following" method, where areas of shaded ground vegetation are eliminated first, and tree crowns are delineated by proceeding from one such area to the next by forming "valleys" of low reflectance valued pixels. This algorithm is then followed by a second, rule-based algorithm to further delineate crown boundaries.

Radiata pine does not have a narrow, regular, conical crown. The branches in the upper half of the crown grow upwards, and although height growth is vigorous, apical dominance can easily be lost if the main shoot is damaged. Double or multiple leaders can occur. From above, the tips of branches of the topmost branch cluster can easily be mistaken for individual trees under some circumstances. The crowns are seldom circular in shape, because branches grow into gaps or areas of less crown competition and quickly become large.

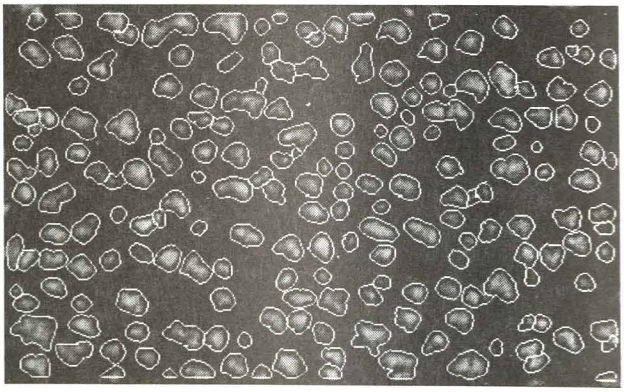
These initial trials found that Gougeon's method holds promise. Using infrared photographs was a useful first start, rather than color photography, because there was a loss of resolution of the lower branches, and the central tallest portion of the crown became more readily observable in contrast to the dark lower periphery. To date, we have implemented the method, with some modifications to the rule-based algorithms specific for radiata pine, and have made subjective comparisons with the original aerial photographs. Figure 2 shows the original infrared photograph, the outcome of the method, and an overlay of the edges of the delineated crowns with the original color photograph. Future work will involve a more rigorous testing over a range of conditions. From the air, the crowns of a stand of radiata pine change dramatically through time. Following thinning, there are large gaps between crowns, and it has been suggested that shortly after the final thinning may be the best time to acquire photography to locate individual trees. Shortly before harvesting, a second image could be acquired, and the



a: Original infra-red image



b: Output from the Rule-Based Algorithm



c: Edge of the successfully delineated crowns obtained from the Rule-Based Algorithm over the original image

Figure 2.—*Automatic delineation of the locations of individual radiata pine trees.*

analysis repeated, making use of the first estimate. Given even radiata's inability for its leader to move far from its original position, we believe the individual tree location problem is solvable at an economic cost.

INVENTORY DURING HARVEST

During the harvest, short-term log allocation planning attempts to ensure that equipment is optimally used and that all product commitments are being met. The situation changes rapidly and these plans are updated weekly. New Zealand harvesting emphasizes value recovery, that is obtaining the maximum value from the coupe by optimum bucking while meeting all constraints imposed by past sales and existing production commitments. Optimally planning which set of bucking instructions to give to one of many logging gangs or machines and the subsequent control and monitoring of performance requires detailed information about the trees that are to be cut over the next day or week. Some of this information can come from pre-harvest inventory and from the geospatial analysis. A major source of information is the immediate-past yield from the coupe. These data can be collected by a log-stocks and delivery information system. Real-time information of the trees currently being harvested can be collected by on-board computers of processors or by electronic calipers used by motor-manual logging gangs as they are bucked. A current research topic is how best to integrate these sources of data, and then provide the information in a practical decision support system. Empirical or hierarchical Bayes procedures (Green and Strawdernan 1992, Burk and Ek 1982) are being investigated as a method of defining what amount of weight to give to each of the sources of information.

CONCLUSIONS

Defining the most appropriate markets and then improving the allocation of log products to current commitments offer the potential to greatly improve the profitability of New Zealand's production forests. Good management needs good information. Pre-harvest inventory has increased in use, especially over the last decade, and this increase has generated a greater demand for more precise and spatially accurate information about the potential yield of log products. New electronic measurement equipment such as ultra-sound or laser hypsometers and computerized calipers, new ways of using photogrammetry incorporated into mapping workstations, and geostatistical and image-processing systems offer the means to provide that information economically.

In the near future, it should be possible to describe the potential recoverable volumes in more detail than is possible by the inventory systems currently in use, and to give indications, at least, of the geographic location of potential log products within a stand or a coupe. Information about the forest as a warehouse should be available in quantitative form and be suitable for input for log allocation and wood flow decision support systems.

ACKNOWLEDGMENTS

The work described above is being carried out by researchers from the New Zealand Forest Research Institute Limited, particularly R. Brownlie, M. Budianto, J. Ellis, J. Firth, A. Gordon, J. Grace, S. Hitchcock, B. Hock, M. Lawrence, N. Mein, and D. Pont. Close collaboration with Dr. W. Carson of OSU, Dr. C. Trotter, of Landcare Research NZ, and Dr. E. Tomppo of the Finnish Forest Research Institute is acknowledged. Funding has been provided by the New Zealand Foundation for Research, Science, and Technology and by the New Zealand forest industry.

This manuscript has been reviewed by Dr. G. Murphy and Ms. B.K. Höck, Scientists, New Zealand Forest Research Institute Limited, Sala Street, Private Bag 3020, Rotorua, New Zealand.

LITERATURE CITED

Burk, T.E.; Ek, A.R. 1982. Application of empirical Bayes/James-Stein procedures to simultaneous estimation problems in forestry. Forest Science. 28(3): 753-771.

Cossens, G.P. 1996. Optimisation of short term log allocation. Lincoln, NZ: Lincoln University. 124 p. M.S. thesis.

Deadman, M.W.; Goulding, C.J. 1979. A method for assessment of recoverable volume by log types. New Zealand Journal of Forestry Science. 8(2): 225-239.

Dralle, K.; Rudemo, M. 1996. Stem number estimation by kernel smoothing of aerial photos. Canadian Journal of Forest Research. 26 (7): 1228-1236.

Gordon, A.D.; Lawrence, M.E.; Pont, D. 1995. Assessing the potential log yield of stands prior to harvesting. In: Bren, L.; Greenwood, C., eds. Applications of new technology in forestry, conference proceedings; 1995 April; Ballarat. Canberra, Australia: Institute of Foresters of Australia: 193-200.

Gougeon, F.A. 1995. A crown following approach to the automatic delineation of individual tree crowns in high spatial reolution aerial images. Canadian Journal of Remote Sensing. 21(3): 274-284.

Gougeon, F.A. 1997. A locally adaptive technique for forest regeneration assessments from high resolution aerial images. Paper presented at the 19th Canadian Remote Sensing symposium; 1997 May 24-30; Ottawa, Canada.

Goulding, C.J.; Deadman M.W.; Lawrence, M.E. 1993. Assessing stem qualities and using dynamic programming to predict log-product volumes in inventory. In: Nyyssonen, A.; Poso, S.; Rautala, J., eds. Proceedings of Ilvessalo symposium on National forest inventories; 1992 August; Helsinki. Finnish Forest Research Institute Research Paper. 444: 171-178.

Green, E.J.; Strawderman, W.E. 1992. A comparison of Hierarchical Bayes and empirical Bayes methods with a forestry application. Forest Science. 38 (2): 350-366.

Gunnarson, F.; Holm, S.; Holmgren, P.; Thuresonn, T. 1998. On the potential of kriging for forest management planning. Scandinavian Journal of Forest Research. 13 (2): 237-245.

Höck, B.K.; Payn, T.W.; Shirley, J.W. 1993. Using a geographic information system and geostatistics to estimate site index of *Pinus radiata* for Kaingaroa forest. New Zealand Journal of Forestry Science. 23: 264-277.

Holmgren, P.; Thuresson, T. 1998. Satellite remote sensing for forestry planning - a review. Scandinavian Journal of Forest Research. 13 (1): 90-110.

Puumalainen, J. 1998. Optimal cross-cutting and sensitivity analysis for various log dimension constraints using dynamic programming approach. Scandinavian Journal of Forest Research. 13 (1): 74-82.

Tomppo, E. 1996. Multi-source National Forest Inventory of Finland. In: Paivinen, R.; Vanclay, J.; Miina, S., eds. New thrusts in forest inventory, XXth IUFRO world congress; 1995 August 6-12; Tampere. Joensuu: European Forestry Institute, Proceedings 7: 27-41.

Tomppo, E.; Katila, M.; Goulding, C.J. 1996. Applying Finnish multisource inventory techniques with New Zealand preharvest inventory data. In: Paivinen, R.; Vanclay, J.; Miina, S., eds. New thrusts in forest inventory, XXth IUFRO world congress; 1995 August 6-12; Tampere. Joensuu: European Forestry Institute, Proceedings 7: 185-203.

Trotter, C.M.; Dymond, J.R.; Goulding, C.J. 1997. Estimation of timber volume in a coniferous plantation forest using Landsat TM. International Journal of Remote Sensing. 18 (10): 2209-2225.

Late-Successional Forests and Northern Spotted Owls: How Effective is the Northwest Forest Plan?

Miles Hemstrom and Martin G. Raphael

Abstract.—This paper describes the late-successional and old-growth forest and the northern spotted owl effectiveness monitoring plans for the Northwest Forest Plan. The effectiveness monitoring plan for late-successional and old-growth forests will track changes in forest spatial distribution, and within-stand structure and composition, and it will predict future trends. Spatial patterns of forest types will be monitored using remotely sensed imagery. Within-stand structure and composition will be tracked on an extensive set of permanent sample plots established on a grid across the region. Trends in landscape pattern and within-stand structure will be estimated using succession models. A first-instance monitoring report will be available to forest managers in the year 2000. The effectiveness monitoring plan for the northern spotted owl has three primary components. First, an annual rate of population change will be estimated using results of mark/recapture demographic studies on eight large (> 1,000 km^2) study areas distributed throughout the species' range. Second, the rate of change of suitable nesting and foraging habitat will be estimated, as classified from vegetation maps obtained from satellite imagery and assessed at 10-year intervals. Finally, we will attempt to develop predictive models relating changes in owl populations to changes in the amount and distribution of habitat. If these models are successful, we will cut back on the demographic studies and rely on model predictions based on habitat condition. If the models are not successful, we will continue to rely on the demographic studies to track population trends.

The Northwest Forest Plan (ROD 1994) addresses management and conservation of late-successional and old-growth forests on federal lands within the range of the northern spotted owl (*Strix occidentalis caurina*, fig. 1). The plan rests on an assessment of late-successional and old-growth forests and associated species within the range of the northern spotted owl in Oregon, Washington, and northern California (FEMAT 1993) and an ensuing environmental impact statement (FSEIS 1994). Late-successional and old-growth forests provide habitat for northern spotted owls, marbled murrelets (*Brachyramphus marmoratus*), and many other species. The Northwest Forest Plan requires monitoring the status of late-successional and old-growth forests, northern spotted owl, and marbled murrelet over a large landscape (over 10 million ha of federal land) for a long period of time (decades to centuries). Effectiveness monitoring plans provide methods for accomplishing this task (Hemstrom *et al.* in press, Lint *et al.* in press, Madsen *et al.* in press). This paper describes the late-successional and old-growth forest and northern spotted owl monitoring plans. These two effectiveness monitoring plans are part of a larger effort to monitor the effectiveness of the plan (Mulder *et al.* in press).

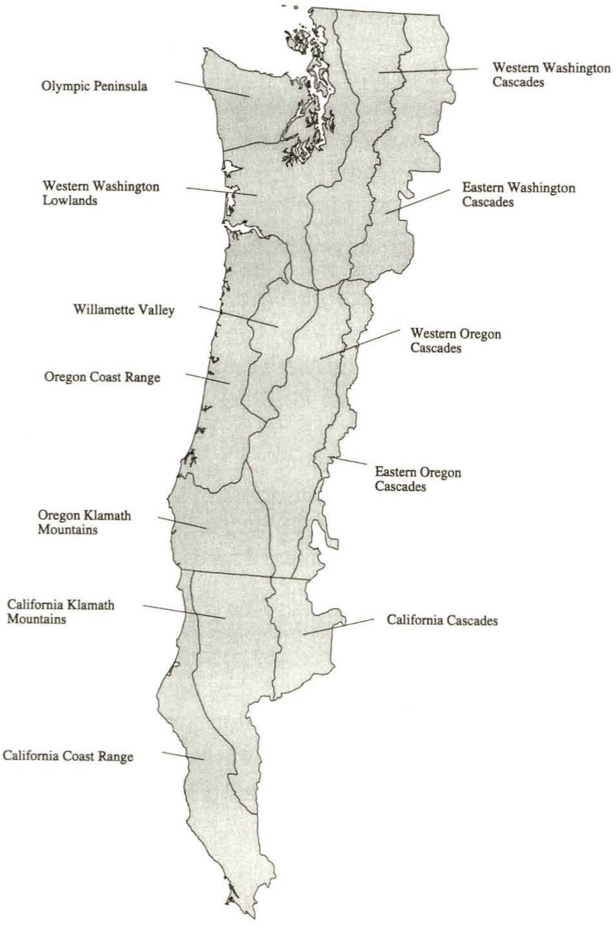


Figure 1.—*Physiographic provinces in the Northwest Forest Plan area (Hemstrom* et al. *in press, used by permission).*

Regional Ecologist, USDA Forest Service, Pacific Northwest Region, Portland, OR, USA; and Research Wildlife Biologist, USDA Forest Service, Pacific Northwest Research Station, Olympia, WA, USA, respectively.

LATE-SUCCESSIONAL AND OLD-GROWTH FOREST MONITORING

Two Views of Late-Successional and Old-Growth Forest

Late-successional and old-growth forest can be described from remotely sensed information about upper canopy features "as seen from above," such as canopy cover, the size of tree crowns, and inferences about tree diameter, canopy structure (single versus multiple layers), and, to a very limited extent, tree species (Cohen and Spies 1992). The size class of the overstory, an indication of overstory canopy complexity, and the dominance by conifers or deciduous species will be mapped using Landsat-TM imagery and used to analyze spatial features of late-successional and old-growth forests.

Late-successional and old-growth forest can also be examined from field plot data. Several stand-scale structural elements will be used to characterize late-successional and old-growth forests: live old-growth trees, standing dead trees, fallen trees or logs, canopy layers, smaller understory trees, canopy gaps, and understory patchiness (Franklin *et al.* 1981, FEMAT 1993). Structural characteristics of old forests vary with environment, vegetation type, disturbance regime, and developmental stage. A partial set of stand-scale definitions of old-growth conditions is available (USDA Forest Service 1992, USDA Forest Service 1993a). Note that "old growth" is a subset of late-successional and old-growth forest. Late-successional and old-growth forest, as defined in the FEMAT report (1993) and the FSEIS (1994), includes mature and old forests.

Because definitions, attributes, and scale differ between remotely sensed and plot-based analyses of late-successional and old-growth forest, estimated amounts of late-successional and old-growth forest are also likely to differ. Remote sensing information allows analysis of spatial features, while plot data provide information about stand-scale structure and composition. A uniform grid of permanent field plots for the measurement of stand-level attributes has been established on USDA Forest Service and USDI Bureau of Land Management lands in the plan area (Max *et al.* 1996). Estimates of late-successional and old-growth forest amounts can be derived from these data using stand-based definitions. Because permanent plot methods are easier to repeat over time, they provide the most accurate estimators of late-successional and old-growth forest amount. Although remote sensing and plot views can be compared (Czaplewski and Catts 1992), they are not the same.

Monitoring Approach

The indicators for late-successional and old-growth forest effectiveness monitoring come from a conceptual model (fig. 2) that links ecosystem process and function to stand structure and composition and to biological diversity (Hemstrom *et al.* in press). Because ecosystem process, function, and biological diversity are difficult to monitor directly, several stand composition and structure attributes were chosen as indicators. Monitoring questions hinge on the conceptual model and allow quantitative answers. The monitoring plan also assumes that managers need to understand why changes occur, hence the inclusion of a monitoring question on sources of change.

Monitoring Questions:

1. What are the distribution and amount of forest classes, including late-successional and old-growth forest, from remotely sensed information and from plot data?
2. What is the stand-size distribution, stand interior area distribution, and interstand distance distribution of late-successional and old-growth forest at the large landscape scale?
3. What are the sources (human uses, fire, insects and pathogens, wind, growth, succession, regeneration, exotic species and others) of change?

Indicators

Monitoring indicators were chosen from composition and structure attributes in the conceptual model. Three kinds of indicators will be examined: (1) large landscape-scale indicators that can be addressed through analysis of remotely sensed imagery, (2) stand-scale indicators that can be addressed through analysis of field plots, and (3) change agent indicators.

Large Landscape-Scale Indicators:

1. Amount: The acreage of land meeting forest class definitions by physiographic province by plant community and land management allocation.
2. Distribution: The distribution of land by forest class as depicted in a map.
3. Stand size: The areal extent of stands of vegetation that meet canopy structure and composition criteria for remotely sensed late-successional and old-growth forest classes.

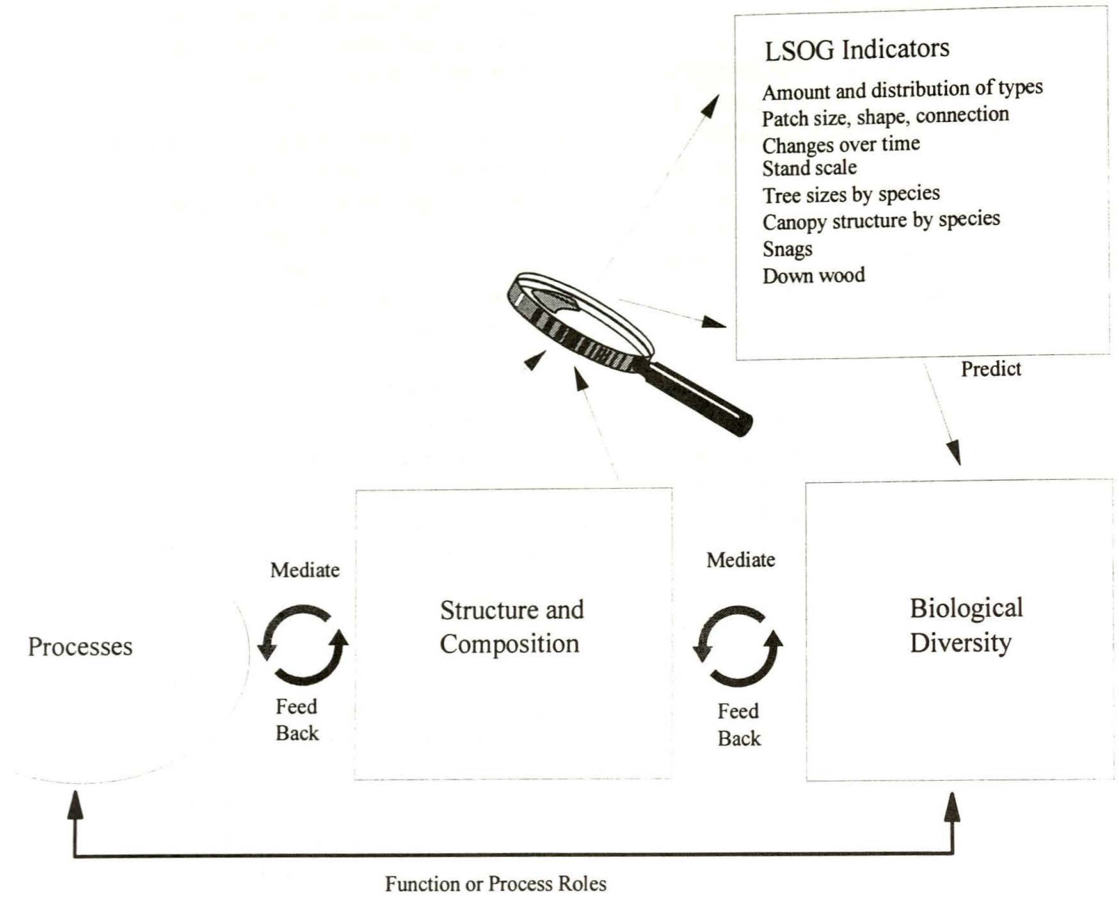

LSOG Indicators
Amount and distribution of types
Patch size, shape, connection
Changes over time
Stand scale
Tree sizes by species
Canopy structure by species
Snags
Down wood
Predict
Mediate
Processes
Structure and Composition
Feed Back
Mediate
Biological Diversity
Feed Back
Function or Process Roles

Figure 2.—*Late-successional and old-growth forest effectiveness monitoring conceptual model (Hemstrom* et al. *in press, used by permission).*

4. Stand interior area: Indices of stand shape (edge to area, fractal dimension, and so forth) are often hard to relate to specific habitat issues. Interior core area of stands, after buffering high contrast edges, will be used as an index of stand shape. Interior core area will be analyzed from remotely sensed data using a buffer of 100 m from late-successional and old-growth forest edges with nonforested and small, single-storied forest classes. Other edge conditions may be analyzed, if needed. Chen *et al.* (1992) found edge effects extending more than 400 m in some cases. Most effects seem to occur within 100 m, however.
5. Interstand distance: The distance between late-successional and old-growth forest stands for the region and for each province by plant community will be displayed in a frequency distribution or cumulative distribution function.

Stand-scale structural and compositional attributes summarized from permanent field plots include:

1. The forested area that meets forest class definitions and ground-based definitions of late-successional and old-growth forest (e.g., USDA Forest Service 1992, USDA Forest Service 1993b).
2. Tree diameter class distribution, canopy structure and height class distribution, snag height and diameter distribution, and down woody debris amounts and sizes on a per area basis for different environments within each physiographic province.

Other attributes that may be useful for characterizing late-successional and old-growth forest will likely emerge from research on stand-scale characteristics, ecological process, and function. Stand age, where it can be determined, may be important for some species (Halpern and Spies 1995). Ongoing research indicates that the spatial arrangement of structure at the stand scale may be important for old-growth function (J. Franklin, University of Washington, personal communication). These may be included in future analyses.

Sources of Change

Sources of change will be tracked from both remotely sensed information and permanent grid plot data. Remotely sensed information will not generally allow determination of the change agent, except possibly for timber harvest and large, intense fires. Most information about change agents will come from permanent field plots. Data recorded on each plot include causes of tree damage (such as fire, logging, insects, and disease). These data will be summarized to quantify causes of change.

Change in late-successional and old-growth forest amounts and spatial distribution as detected in remotely sensed images can also come from changes in methods used to process remotely sensed data. It will be important to quantify changes in spatial attributes due to methods alone. In this sense, remotely sensed information about late-successional and old-growth forest attributes is less repeatable than information from permanent field plot remeasurement.

Predictive Models

Changes in late-successional and old-growth forests may take decades or centuries to become evident. Since the time lag between management actions and the development of late-successional and old-growth forest is so long, models would provide an early indication of the need for any adjustments in the plan. Forest growth and development will be projected using stand growth simulation models. Projected trends will provide an early indication, subject to review, about the direction of forest development. Recalibration of existing models and development of new models will likely be necessary.

Baselines

Detection of trends depends on a baseline for comparison. Baselines will be established for remotely sensed and stand scale indicators. A baseline map will be developed using the most recent Landsat thematic mapper imagery available (generally 1996) and will be analyzed for the first monitoring report. Imagery from 1996 will be accepted as approximating the conditions at the start of the Northwest Forest Plan implementation even though some change would have occurred in the 2 years between the date of Forest Plan adoption and the date of the remotely sensed imagery.

A stand-scale baseline will be established from the permanent grid plots distributed across the region by the end of 1998. In addition, maps and descriptions of the strata used in the first report (physiographic provinces, plant communities, land allocations) will be archived for future use. These baseline information sets should be housed in a permanent facility, accessible to anyone who needs to use them.

The FEMAT report (1993) and the FSEIS (1994) also call for comparing existing late-successional and old-growth forest conditions (amounts, distribution, connection, process, function) to long-term averages and long-term average lows. These are defined as the late-successional and old-growth forest conditions in the last several centuries. The FEMAT report and the FSEIS suggest developing this information through fire history studies, stratified by province and plant community, but these studies do not exist for much of the region. A retrospective analysis of conditions before FEMAT is not required for the first monitoring report. Analysis of the long-term averages could be used in subsequent reports as research is completed.

Quality Assurance

Accuracy assessments must be performed on any maps used in late-successional and old-growth forest analysis to understand the confidence interval associated with any results. A random sample of the permanent field plots is remeasured in the field to quantify their accuracy. A random set of permanent field plots will be reserved and used for an accuracy assessment of the vegetation maps (Czaplewski and Catts 1992). Imagery used for developing vegetation maps will be of generally similar vintage across the landscape being analyzed to reduce the effects of changes that might occur within short time frames (fire or logging, for example).

Link to Decisionmaking

A report will be generated every 5 years, more often if needed, detailing the status of threshold attributes and their projected 50- and 100-year trends in comparison to FSEIS (1993) expectations. Attributes that depart significantly from projected trends (more than 10 percent) will be highlighted. Deviations of important attributes from projected trends will trigger a variety of actions, ranging from review of stand succession models and mapping methods, to an examination of the Forest Plan and its implementation. Since results may require interpretation, a panel of scientists, managers, and others will review results and develop interpretations and recommendations for land managers.

How Will We Know if the Plan is Succeeding?

The FEMAT report (1993) and the FSEIS (1994) provide a basis for gauging success. They discuss abundance and ecological diversity, process and function, and connectivity outcomes for late-successional and old-growth forest.

Thresholds provided in these documents are general and regionwide, and they apply only to federal lands. Outcomes in the FEMAT report and the FSEIS link to the likelihood of maintaining both the viability of late-successional and old-growth forest-related species and the likelihood of maintaining a functional, interacting late-successional and old-growth forest ecosystem on federal lands. Current conditions and trends from monitoring analysis will be compared to outcomes and conditions in these documents to provide a basis for judging the success of the Northwest Forest Plan in meeting late-successional and old-growth forest objectives. In addition, models will be used to project forest conditions into the future, since it takes decades or centuries for young stands to develop into late-successional and old-growth forest. Modeled future trends will be compared to projections in the FEMAT report and the FSEIS. A first monitoring analysis and report, generated in 1999-2000, will provide the starting point or first instance summary.

Research Needed

Several important topics should be investigated to refine our ability to monitor late-successional and old-growth forests. These include: (1) more refined uses of, and sources of error in, remotely sensed information to map forest structure and composition; (2) expected rates of transition among forest types over time in different environments; (3) long-term baseline conditions; (4) refined definitions or indices of old-growth forest characteristics; (5) better models to project long-term forest development and spatial patterns; and (6) basic research of the relations between processes, functions, composition, structure, and biological diversity.

NORTHERN SPOTTED OWL MONITORING

The objective of the northern spotted owl effectiveness monitoring plan is to assess trends in spotted owl populations and habitat on federal lands throughout the range of the owl in Washington, Oregon, and California (fig. 1). Before implementation of the Northwest Forest Plan, studies of population trends of the northern spotted owl indicated that the owl's population was declining at a mean rate of 8.4 percent per year (95 percent confidence interval = 0.7 to 8.4 percent) and that the rate of decline had been accelerating (Burnham *et al.* 1996). The forest plan was designed, in part, with the intent to arrest, or possibly reverse, this downward trend. The primary monitoring question is whether the Northwest Forest Plan is successful in halting the downward trend in the spotted owl population (Forsman *et al.* 1996) and in restoring habitat conditions necessary to support a well-distributed and stable population of owls.

Monitoring Approach

Monitoring Questions

Given the overall objectives stated above, the monitoring plan addresses the following general questions:

1. Will implementation of the Forest Plan reverse the declining population trend and maintain the historic geographical distribution of the northern spotted owl?
   A. What is the trend in rates of demographic performance (adult survival, reproduction, turnover, finite rate of population change)?
   B. Can the status and trend in spotted owl abundance and demographic performance be reliably predicted from distribution and abundance of habitat?
2. Is spotted owl habitat being maintained and restored as prescribed under the Forest Plan?
   A. What is the trend in the amount and distribution of habitat?
   B. What is the trend in the amount and distribution of dispersal or foraging habitat?

Conceptual Model

An initial step in designing a monitoring strategy was the development of a conceptual model to help sharpen understanding of the underlying processes that govern the dynamics of the spotted owl population. The conceptual model focuses on habitat change, both in the amount and in its pattern or level of fragmentation. Scale is an important consideration and the design team developed two related models, one at the stand (or home range) level and one at the landscape (or subpopulation) level. As described above for the late-successional and old-growth forest (LSOG) plan, the models have several components including stressors (those processes that act on habitat or individual animals), effects (expected changes on habitat or owls caused by the stressors), and indicators (those attributes of the system that are amenable to measurement and that reflect the effects). The conceptual model developed for the spotted owl focuses on habitat change as well as population change (illustrated in figure 3 for the stand or home range level).

At the home range scale (fig. 3), habitat stressors ultimately affect birth and death rates of individual owls. The proximate responses to disturbance include changes in the density of large living and dead trees and logs as well as changes in the diameter distribution of these features. These attributes affect the density of nest sites and the quality of foraging habitat. These features, in turn, lead to changes in reproductive success and survival of individual owls.

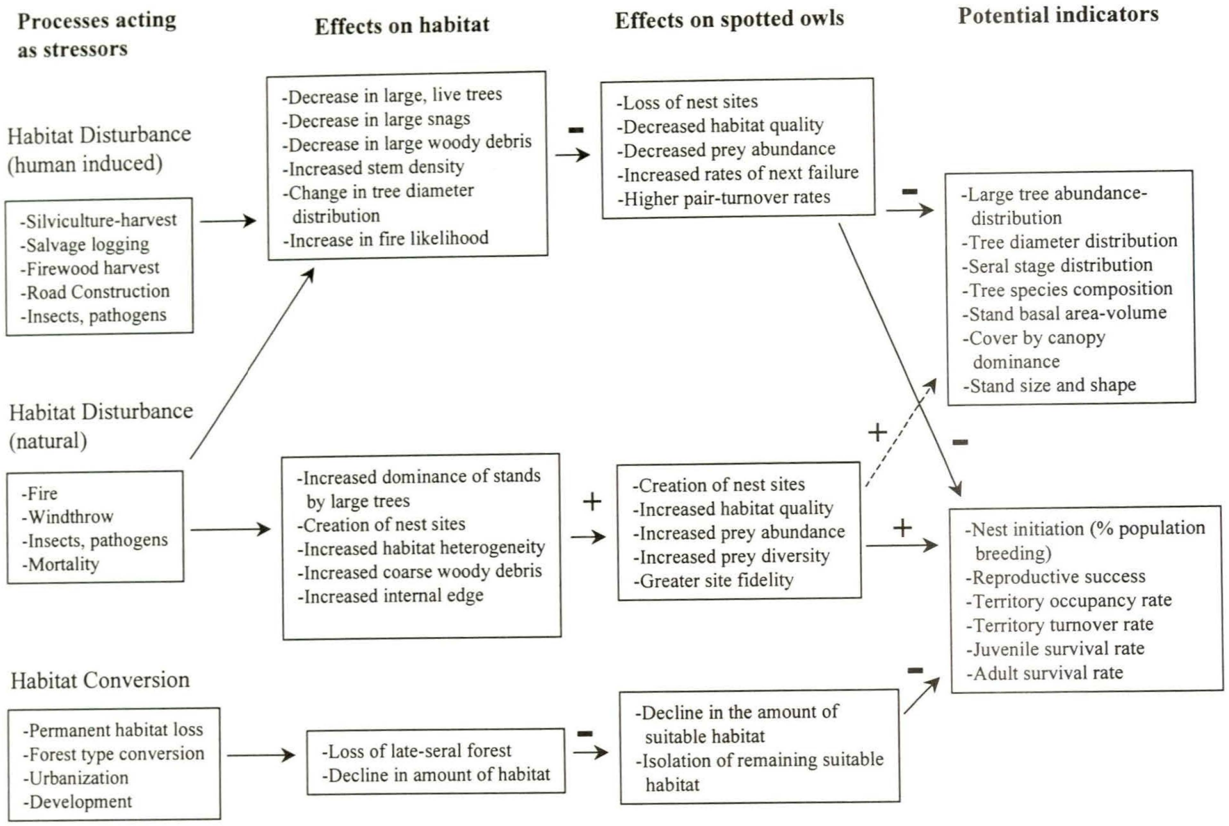

Processes acting as stressors
Effects on habitat
Effects on spotted owls
Potential indicators
Habitat Disturbance (human induced)
-Silviculture-harvest
-Salvage logging
-Firewood harvest
-Road Construction
-Insects, pathogens
-Decrease in large, live trees
-Decrease in large snags
-Decrease in large woody debris
-Increased stem density
-Change in tree diameter distribution
-Increase in fire likelihood
-
-Loss of nest sites
-Decreased habitat quality
-Decreased prey abundance
-Increased rates of next failure
-Higher pair-turnover rates
-
-Large tree abundance-distribution
-Tree diameter distribution
-Seral stage distribution
-Tree species composition
-Stand basal area-volume
-Cover by canopy dominance
-Stand size and shape
Habitat Disturbance (natural)
+
-
-Fire
-Windthrow
-Insects, pathogens
-Mortality
-Increased dominance of stands by large trees
-Creation of nest sites
-Increased habitat heterogeneity
-Increased coarse woody debris
-Increased internal edge
+
-Creation of nest sites
-Increased habitat quality
-Increased prey abundance
-Increased prey diversity
-Greater site fidelity
+
-Nest initiation (% population breeding)
-Reproductive success
-Territory occupancy rate
-Territory turnover rate
-Juvenile survival rate
-Adult survival rate
Habitat Conversion
-
-Permanent habitat loss
-Forest type conversion
-Urbanization
-Development
-Loss of late-seral forest
-Decline in amount of habitat
-
-Decline in the amount of suitable habitat
-Isolation of remaining suitable habitat

Figure 3.—*Northern spotted owl effectiveness monitoring conceptual model at the home range scale (Lint* et al. *in press, used by permission).*

Indicators

A list of potential indicators was derived from these conceptual models (fig. 3). Desirable attributes of candidate indicators include:

1. The indicator reflects fundamental population processes and changes in stressor levels (habitat change).
2. The indicator is representative of the state of the population.
3. The indicator is measurable and can be quantified at reasonable cost.
4. The indicator demonstrates a low level of natural variability so that changes can be distinguished from background variation.

Primary Components of the Monitoring Strategy

The monitoring strategy for the northern spotted owl has three primary components. First, the team will estimate demographic trends from a sample of marked birds monitored on eight large study areas. Second, the team will estimate trend in amount and distribution of habitat based on analysis of satellite imagery. Third, the team will develop predictive models that relate demographic trends to trends in habitat condition. If these models are successful, predicted population trends based on habitat condition will be emphasized.

Population Monitoring

Three alternative methods for monitoring spotted owl populations were evaluated. The first, based on mark-recapture methods, provides precise estimates of rates of juvenile and adult survival and reproduction (see *Franklin et al.* 1996 and Raphael *et al.* 1996 for methods and rationale). A second alternative would be to estimate population size each year from a set of random calling stations distributed throughout the owl's range. A third method would require a total count of all owls each year in selected intensive study areas. For each of the latter two methods, population change would be estimated directly from changes in estimated population size from one year to the next (or over a series of years).

After evaluating the costs and reliability of each of these alternatives, the spotted owl monitoring team selected the mark-recapture approach. Such studies were already underway and formed the basis for the available estimates of population status (Forsman *et al.* 1996). An additional critical factor in selecting this approach was its utility in supporting development of predictive models. Detailed information on demographic rates would be available for a large sample of spotted owls. For each owl, characteristics of habitat quality and distribution could also be obtained and used as the basis for model development.

Demographic data will be obtained from eight demographic study areas (fig. 4) varying in size from about 1,000 km^2 to over 8,000 km^2. Although these study areas do not cover all of the provinces or ecological conditions across the range of the owl, they do represent a large area that spans a wide range of habitat conditions. Estimates of survival reproductive rates will be analyzed and summarized for individual study areas at the end of each year. A more comprehensive meta-analysis (e.g., Burnham *et al.* 1996) will be conducted every 3 years (starting December 1998).

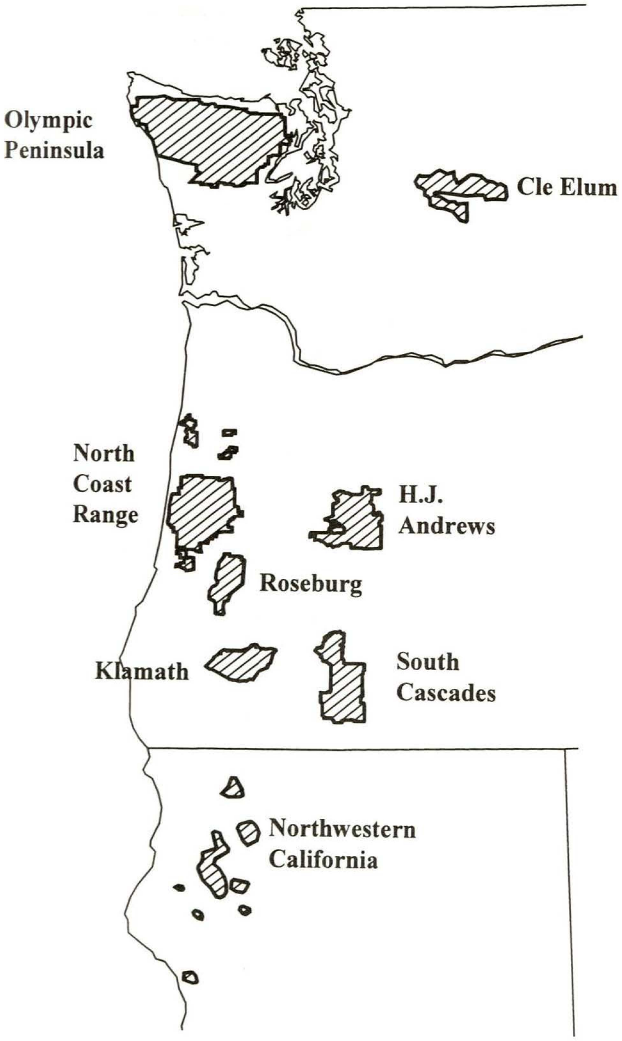


Figure 4.—*Proposed demographic study areas in the Northern spotted owl effectiveness monitoring plan (Lint* et al. *in press, used by permission).*

Habitat Monitoring

The basic information needed for rangewide monitoring of spotted owl habitat is a set of digital map layers that will be managed in a geographic information system. Habitat monitoring will be based on the same vegetation map that will be used by the LSOG monitoring group. Federal land management agencies in the Pacific Northwest Region have committed necessary resources to produce this rangewide map of vegetation. To monitor spotted owl habitat, appropriate structural classes and species of vegetation will be identified and used to classify both nesting and dispersal (or foraging) habitat. Habitat condition and trend will be estimated every 5 years after a baseline map is developed. Monitoring over time will allow estimates of change in the amount and distribution of spotted owl habitat. Habitat reports will be generated showing acres of habitat by land allocation and will include metrics describing landscape pattern. Attributes will include estimates of patch composition, mean patch size, distance between patches, patch shape, and other measures of landscape pattern.

Predictive Modeling

The spotted owl monitoring plan assumes a transition from direct population monitoring to a habitat-based monitoring strategy. This will be possible only if relationships can be established between trends in owl populations and trends in amount and pattern of habitat. Therefore, the monitoring team will focus on developing models that relate relative abundance and/or demographic rates to the amount and distribution of habitat as derived from the habitat monitoring module. Development of these models will take place over the next 5 years. The advantages of moving toward a habitat-based monitoring strategy include:

1. Habitat monitoring can build from existing forest inventory programs as part of ongoing work.
2. Estimating trends in vegetation structure and composition represents a prospective, rather than retrospective, approach to ecological monitoring.
3. Monitoring vegetation change is more cost-effective that directly monitoring owl populations.

We recognize that the expected correspondence between owl trends and attributes of vegetation will have uncertainty. There are a number of possible limitations to this approach, including:

1. Some variation in populations is due to other factors and will be missed if monitoring relies on inferences from habitat change.
2. Changes in habitat may not predict changes in populations with sufficient reliability.
3. Satellite-based habitat maps may not measure the

fine-scale attributes that distinguish higher quality habitat (such as snags for nest sites or logs for prey cover).

These limitations may preclude replacing the demographic approach with the habitat approach. The monitoring team will evaluate the reliability of predictive models and decide whether they will perform as expected. The models will be tested through a series of validation studies in areas outside the demographic study areas. If the validation work indicates the models are not successful, then monitoring will rely on demographic data over the long run, supplemented with estimates of trend in broad habitat attributes.

Research Needs

The distinction between monitoring and research is not as clear as many would think. As part of any monitoring program, a number of research questions and needs are apparent. For the northern spotted owl monitoring plan, we have identified a number of research topics that are key to implementation of the plan. These research needs (in no particular order) include: (1) the relations between habitat structure, prey ecology, individual owl home range, and variation in vital rates of owl populations, (2) owl habitat characteristics and the implications of using vegetation attributes for habitat classifications, (3) role of habitat amount, type, and pattern on the speed, pattern, and survival of dispersing juvenile owls, (4) the use of remotely sensed vegetation information to identify and map spotted owl habitat, and (5) an assessment of a random census plot technique for estimating owl population trends.

CONCLUSION

Monitoring the effectiveness of the Northwest Forest Plan is a long-term process. Decades will pass before land managers know for sure whether or not the plan is producing the intended results. During the next several decades, careful documentation of methods and processes will be necessary if managers of the future are to understand monitoring results. Data will have to be maintained and transformed as computer systems and databases evolve. Land management agencies must be dedicated to a long-term investment in effectiveness monitoring if we intend future managers to understand what happened to late-successional and old-growth forests and related species and why it happened. None of this will be inexpensive, nor will it happen unless effectiveness monitoring becomes a normal, ongoing part of the land management business.

ACKNOWLEDGMENTS

The authors thank the members of the various effectiveness monitoring groups for their contributions to the concepts described in this paper. This paper is a summary of the more detailed presentations in the monitoring plan. In particular, we thank J. Lint who led the northern spotted owl monitoring group. The following people reviewed this manuscript: Joe Lint, USDI Bureau of Land Management, Roseburg, OR, USA, and Warren Cohen, USDA Forest Service, Forestry Sciences Laboratory, Corvallis, OR, USA.

LITERATURE CITED

Burnham, K.P.; Anderson, D.R.; White, G.C. 1996. Meta-analysis of vital rates of the northern spotted owl. Studies in Avian Biology. 17: 92-101.

Chen, J.; Franklin, J.F.; Spies, T.A. 1992. Vegetation responses to edge environments in old-growth Douglas-fir forests. Ecological Applications. 2: 387-396.

Cohen, W.B.; Spies, T.A. 1992. Estimating structural attributes of Douglas-fir/western hemlock forest stands from Landsat and SPOT imagery. Remote Sensing of Environment. 41: 1-17.

Czaplewski, R.L.; Catts, G.P. 1992. Calibration of remotely sensed proportion or area estimates for misclassification error. Remote Sensing of Environment. 39: 29-43.

FEMAT. 1993. Forest ecosystem management: an ecological, economic and social assessment. Report of the Forest Ecosystem Management Assessment Team. Portland, OR: USDA Forest Service, USDC National Marine Fisheries Service, USDI Bureau of Land Management, USDI National Park Service, and USEPA.

Forsman, E.D.; DeStefano, S.; Raphael, M.G.; Gutiérrez, R.J. 1996. Demography of the northern spotted owl. Studies in Avian Biology. 17: 1-12.

Franklin, A.B.; Anderson, D.R.; Forsman, E.D.; Burnham, K.P.; Wagner, F.W. 1996. Methods for collecting and analyzing demographic data on the northern spotted owl. Studies in Avian Biology. 17: 12-20.

Franklin, J.F.; Cromack, K., Jr.; Dennison, W.; McKee, A.; Maser, C.; Sedell, J.; Swanson, F.; Juday, G. 1981. Ecological characteristics of old-growth Douglas-fir forests. Gen. Tech. Rep. PNW-118. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 48 p.

Franklin, J.F.; Spies, T.A. 1991. Ecological definitions of old-growth Douglas-fir forests. In: Ruggiero, L.F.; Aubry, K.B.; Carey, A.B.; Huff, M., tech. coords. Wildlife and vegetation of unmanaged Douglas-fir forests. Gen. Tech. Rep. PNW-285. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 61-69.

FSEIS. 1994. Final supplemental environmental impact statement on management of habitat for late-successional and old-growth related species with the range of the northern spotted owl. Portland, OR: USDA Forest Service and USDI Bureau of Land Management.

Halpern, C.B.; Spies, T.A. 1995. Plant species diversity in natural and managed forests of the Pacific Northwest. Ecological Applications. 5: 913-934.

Hemstrom, M.; Kiester, R.; McDonald, P.; Palmer, C.; Spies, T.; Teply, J.; Warbington, R. 1999. Late-successional and old-growth forest effectiveness monitoring plan for the Northwest Forest Plan. Gen. Tech. Rep. PNW-438. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Lint, J.B.; Anthony, R.; Collopy, M.; Forsman, E.D.; Noon, B.R.; Raphael, M.G.; Starkey, E.E. 1999. Northern spotted owl effectiveness monitoring plan for the Northwest Forest Plan. Gen. Tech. Rep. PNW-440. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Madsen, S.; Evans, D.; Hamer, T.; Hensen, P.; Miller, S.; Nelson, S.K.; Roby, D.; Stepanian, M. 1999. Marbled murrelet effectiveness monitoring plan for the Northwest Forest Plan. Gen. Tech. Rep. PNW-439. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Max, T.A.; Schreuder, H.T.; Hazard, J.W.; Oswald, D.D.; Teply, J.; Alegria, J. 1996. The Pacific Northwest Region vegetation and inventory monitoring system. Res. Pap. PNW-493. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 22 p.

Mulder, B.S.; Noon, B.R.; Spies, T.A.; Raphael, M.G.; Olsen, A.R.; Palmer, C.J.; Reeves, G.H.; Welsh, H.H. 1999. The strategy and design of the effectiveness monitoring program for the Northwest Forest Plan. Gen. Tech. Rep. PNW-437. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Raphael, M.G.; Anthony, R.G.; DeStefano, S.; Forsman, E.D.; Franklin, A.B.; Holthausen, R.; Meslow, E.C.; Noon, B.R. 1996. Use, interpretation, and implications of demographic analyses of northern spotted owl populations. Studies in Avian Biology. 17: 102-112.

ROD. 1994. Record of decision for amendments to Forest Service and Bureau of Land Management planning documents within the range of the northern spotted owl, and standards and guidelines for management of habitat for late-successional and old-growth forest related species within the range of the northern spotted owl. Portland, OR: USDA Forest Service and USDI Bureau of Land Management.

USDA Forest Service. 1992. Old growth definitions/descriptions for forest cover types. Internal memo dated June 19, 1992. San Francisco, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Region.

USDA Forest Service. 1993a. A first approximation of ecosystem health. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 109 p.

USDA Forest Service. 1993b. Region 6 interim old growth definition[s] [for the] Douglas-fir series, grand fir/white fir series, interior Douglas-fir series, lodgepole pine series, Pacific silver fir series, ponderosa pine series, Port Orford cedar series, tanoak (redwood) series, western hemlock series. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region.

Assessing Forest Fragmentation Metrics from Forest Inventory Cluster Samples

Christoph Kleinn

Abstract.—Fragmentation of forest area plays an important role in the ongoing discussion of forest dynamics and biological and ecosystem diversity. Among its contributing factors are size, shape, number, and spatial arrangement of forest patches. Several metrics and indexes are in use, predominantly in quantitative landscape ecology. An important area of interest is the assessment of diversity from sample data. This paper presents a sample-based approach to analyzing standard cluster sample data from forest inventories and applying basic considerations of geometrical probabilities. The number and mean size of forest patches can then be estimated under some general assumptions. With this information, a basic characterization of fragmentation is obtained. In a practical example, satisfactory differentiation between subregions of different spatial structure of forest patches could be found. The method also allows the analysis of historic cluster sample data in the absence of corresponding forest cover maps.

Both forest area and its fragmentation are important attributes in forest monitoring. Fragmentation characterizes diversity of the spatial distribution of forests and is related closely to ecosystem diversity, one of the three levels that make up biological diversity. Determining factors are the size, shape, number, and spatial arrangement of individual forest patches. Riiters *et al.* (1995) provide a comprehensive overview of corresponding diversity indices, also called landscape metrics. External factors that affect the quantitative assessment of fragmentation are scale and spatial resolution.

Fragmentation is currently an intensively studied topic in the context of deforestation, the loss of biological diversity, and the loss of ecological functions of forests. In fact, forest fragmentation is evolving into a standard attribute assessed routinely in forest surveys (e.g., Lund 1998). Fragmentation, however, is not only a forestry issue. Most of the relevant contributions in the last years stem from quantitative landscape ecology. Fragmentation information can be used to describe the status and changes of a landscape structure. But there are numerous research activities relating for example, species diversity to changes in landscape structure; thus, data on fragmentation are interesting input in many kinds of models (e.g., Fahrig and Merriam 1985). Beyond the ecological function of forests, forest fragmentation also has economic and socioeconomic implications (e.g., Schelhas and Greenberg 1996).

This study concentrates on the specific issue of assessing fragmentation characteristics through sampling. Normally this is accomplished through analysis of large fixed-area plots in which aspects of fragmentation are observed, inferring with the classical extension-factor-approach from the sample information to the situation in the population (e.g., Hunsaker *et al.* 1994). The present study uses geometric information contained in cluster field samples in forest inventories to estimate two closely related aspects of forest fragmentation: mean patch size and number of forest patches. These estimates can be considered a secondary product of spatial cluster sampling. A more comprehensive treatment of this topic is in preparation (Kleinn 1998).

SAMPLING FOR STRUCTURAL DIVERSITY

Magurran (1988), for example, discusses in general terms the problem of assessing biological diversity through sampling. While the abundance component of species diversity can be estimated without bias, this does not hold for estimating the second constituting factor, species richness. Therefore, sample-based estimates of a number of diversity indices are biased. Comparability, is given only, if at all, when techniques and metrics employed are identical.

As with species diversity, assessing forest fragmentation involves the measurement of several characteristics. This makes issues of consistency and interpretation critical. Most sampling approaches based on fixed-area sample plots (e.g., Hunsaker *et al.* 1994, Traub and Kleinn 1998) provide unbiased estimates of some components, such as the total forest area. For other attributes, such as the number of forest patches, fixed-area sample plots are inadequate. This highlights why, in the assessment of

---

Sub-Unidad de Estadística, Centro Agronómico Tropical de Investigación y Enseñanza, CATIE, Costa Rica.

fragmentation, the estimation of indices is also problematic.

USING SPATIAL CLUSTER SAMPLES TO ASSESS MEAN FOREST PATCH SIZE

Sampling with spatial clusters, in which m points (plots) are arranged in some defined geometry, has a favorable characteristic with respect to spatial analysis. Such clusters are frequently used in large area forest surveys, where plots are, for example, placed at the four corners of a square or at the three "corners" of a half-square. Due to the spatial arrangement of several plots at one sample point, this type of sampling carries geometric information about the study population—not only the information on total forest area as normally analyzed. Using a cluster of m points (plots), some of them will fall completely outside forest, some of them completely inside forest, and a third group will be partly outside forest. This simple classification offers an opportunity to analyze for aspects of fragmentation. A high percentage of clusters completely inside forest is an indication of a fragmentation structure with forest patches that are large compared to the spatial extension of the cluster used. If a large percentage of the clusters intersect with the forest border, a more fragmented spatial distribution pattern exists.

According to this classification of cluster positions relative to forest patches, the region of interest can be subdivided into three classes: complete forest, border, complete nonforest. The cluster sample yields an unbiased estimate of the relative and absolute size of these three subregions, and incidentally an estimate of the probability that, under the given structure of the population, a cluster intersects with a forest border.

We define the position of a square cluster, as used in the case study, by a center point, which is the position of the intersection of its diagonals, where the diagonals define the largest spatial extension of the cluster. Then, only clusters whose center point is not farther than half of the diagonal d from the next forest border have a chance to intersect with it. Half the length of the diagonal defines therefore the width of the border strip on both sides of the forest border. Total width of the border strip is therefore d. However, only in the hypothetical case of a circular cluster with $m \rightarrow \infty$ cluster points and diameter d, will all clusters with center points in the border strip intersect the forest border. For any other cluster shape, this probability is less than 1. In the case of a square cluster, for example, this conditional probability of intersection is

$$P_{is} = \frac{2\sqrt{2}}{\pi} = 0.9003$$

(e.g,. Kleinn 1994). That means that out of all clusters having their center points within the border strip, only 90.03 percent will intersect the borderline between forest and nonforest. The remaining 9.97 percent represent positions where the center point is within the border strip, but the square cluster has an orientation so that no intersection takes place.

For simplicity we assume now that forest and nonforest are separated by a straight line. This is one model assumption for the subsequent calculations. Curvature increases the probability of intersection so that one tends to underestimate this probability under this assumption. The same holds for the assumption that border strips of different forest patches do not overlap. This imposes the condition of a minimum distance between forest patches, which is necessary since the point information on the cluster does not permit a distinction between cluster points that fall in the same forest patch and those that fall in different ones.

Under these assumptions, we are now able to estimate mean forest patch size for any geometric shape of forest patches. For circular and for square shapes, the calculation formulae for mean patch size and for number of patches in the inventory region are given in table 1.

Table 1.—*Calculation formulae for mean patch size* g_m *and mean number of patches* n_m *for square and circular shaped forest patches (Kleinn 1998)*

Shape	g_m	n_m
Circle	$4\pi d^2\left(\frac{\hat{p}}{\hat{p}_s}P_{is}\right)^2$	$\frac{\hat{p}F}{g_{m(circle)}}$
Square	$16d^2\left(\frac{\hat{p}}{\hat{p}_s}P_{is}\right)^2$	$\frac{\hat{p}F}{g_{m(square)}}$

With P_{is}: Conditional probability of intersection of specific cluster shape within borderstrip.
$\hat{p}$: Estimate of proportion of forest cover in the inventory region.
p_s: Estimate of proportion of border strip in the inventory region.
d: Maximum spatial extension of cluster = total width of border strip.
F: Total survey area.

Here, mean patch size is a linear function of $k^2 = \left(\frac{\hat{p}}{\hat{p}_s}P_{is}\right)^2$ useful to compare aspects of fragmentation. k^2 naturally depends on cluster shape and spatial extension, which directly enters via the probability estimate P_{is}.

Example:

In a regional forest inventory in the Northern Zone of Costa Rica, square clusters of length $s = 0.15$ km were used in a 2.5-km square grid, with plots at the four cluster corners. For this study we used only the forest/non-forest information originating from the four corner points of each cluster. For the fragmentation analysis, the region was arbitrarily subdivided into two subregions with obviously different spatial forest distributions. The northern subregion is characterized by a higher forest cover percent and large forest patches, whereas in the southern subregion forest patches are smaller and occur less frequently. Table 2 gives the relevant data and the results according to the formulas given above.

Table 2.—*Baseline data of the example inventory regions and sub-regions to calculate measures of spatial structure*

	Subregion North	Subregion South
Forest cover estimate $\hat{p}$	0.3200	0.1288
Estimated share of border strip $\hat{p}_s$	0.2167	0.1623
Total cluster points	443	456

Values of k^2 increase with increasing fragmentation; high values stem from a small proportion of clusters falling within the border strip, i.e., there are relatively few forest borders and relatively large forest patches. Comparing the northern and southern subregions, the results in table 3 clearly indicate a much more fragmented forest distribution in the southern part with a value of $k^2 = 1.7676$ for the northern and $k^2 = 0.5105$ for the southern subregion. Accordingly, mean patch size is much smaller in the southern subregion with 28.87 ha, compared to the northern subregion with an estimated mean patch size of 99.95 ha.

CONCLUSIONS AND OUTLOOK

Extent of forest fragmentation is of interest in several disciplines. It can be derived from complete maps as given by air photos or satellite images, or it can be based on sample data. This paper presents an assessment using cluster sample data of forest inventories, and applying basic considerations of geometric probabilities.

The numerical results of the case studied showed that the statistic k^2 allows differentiation between fragmentation levels of obviously differently structured subregions. It describes two closely related aspects of forest area spatial fragmentation: mean patch size and number of patches. It is simple to apply and can be used to quantify and compare fragmentation levels of different subregions or of the same region at different points in time.

The method might be interesting because it does not require additional information outside what is available through standard large area forest inventories with cluster sampling. It can therefore be easily applied to past inventories for which no complete coverage through satellite imagery or air photos is available, thus allowing a retrospective analysis of structural diversity.

ACKNOWLEDGMENTS

The author thanks Dr. Oliver Schabenberger, Assistant Professor of Applied Statistics, Michigan State University, and Dr. Pedro Ferreira, Statistician and Director of External Cooperation of CATIE. Costa Rica, for their constructive comments and their critical review of this paper.

Table 3.—*Characteristics of spatial structure, derived from cluster sampling inventory data (Details see text)*

Sub- Region	$\hat{p}$	$\hat{p}_{is}$	*F (km²)*	k^2	Assumed patch shape			
					Circle		Square	
					g_m(km²)	n_m	g_m(km²)	n_m
North	0.3200	0.2167	2768.75	*1.7676*	0.9995	886	1.2726	696
South	0.1288	0.1623	2850.00	*0.5105*	0.2887	1,272	0.3676	999

LITERATURE CITED

Fahrig, L.; Merriam, G. 1985. Habitat patch connectivity and population survival. Ecology. 66: 1762-1768.

Hunsaker, C.T.; O´Neill, R.V.; Jackson, B.L.; Timmins, S.P.; Levine, D.A.; Norton, D.J. 1994. Sampling to characterize landscape pattern. Landscape Ecology. 9(3): 207-226.

Kleinn, C. 1994. Vergleich der Genauigkeit von Anteilsschätzungen mit Linientaxation und Punkteclustern. Forstwissenschaftlices Centralblatt(Hamburg). 113(1994): 277-290.

Kleinn, C. 1998. Assessment of forest fragmentation: estimating mean patch size from standard forest inventory cluster sample data (in preparation).

Lund, G., ed. 1998. IUFRO Guidelines for designing multipurpose resource inventories. IUFRO World Series Vol. 8. IUFRO Secretariat Vienna. 216 p.

Magurran, A.E. 1988. Ecological diversity and its measurement. Chapman and Hall. 179 p.

Riiters, K.H.; O'Meill, R.V.; Hunsaker, C.T.; Wickham, J.D.; Yankee, D.H.; Timmins, S.P.; Jones, K.B.; Jackson, B.L. 1995. A factor analysis of landscape pattern and structure metrics. Landscape Ecology. 10(1): 23-39.

Schelhas, J.; Greenberg, R. 1996. Forest patches in tropical landscapes. Washington, DC: Island Press.

Traub, B.; Kleinn, C. 1998. Fragmentierung und strukturelle Diversität- Quantitative Methoden -. (Submitted to Forstarchiv).

Forest Cover Type, Habitat Diversity, and Anthropogenic Influences on Forest Ecosystems Adjoining the Maasai Mara National Reserve, Kenya

James Legilisho-Kiyiapi

Abstract.—Through combined use of satellite imagery, aerial photographs, and ground truthing, a multilevel assessment was conducted in a forest block that forms a unique dispersal zone to the Maasai Mara National Reserve ecosystem. Results of the survey revealed considerable ecological diversity on an area-scale basis—in terms of ecotypes. Forest types ranged from Afro-montane dry conifer forests to semi-deciduous to dry deciduous forests. Distinct monospecific vegetation zones interspersed by mixed species clusters were delineated within the forest block. Forest edges and, in some cases, open glades within closed canopy forests are dominated by "clustered vegetation" atypical of the well-described savanna woodlands, thought to be heavily influenced by grazing and fire. Although habitat diversity in relatively undisturbed forest areas could be attributed to localized variation in altitude, soil, and drainage conditions, large and varied wildlife populations prevalent in the area as well as increased anthropogenic-related factors in recent years (forest encroachment through settlement and cultivation, forest exploitation, overgrazing, burning by forest-adjacent local populations) are largely responsible for the observed, progressive decline in vegetation diversity, and hence form the basis for design of monitoring systems. These preliminary findings suggest a need for a more detailed integrated survey approach for forest management planning involving local communities.

In the past 2 decades, forestry has taken on a new dimension. The traditional state-controlled and highly centralized forest management practices that restricted or even denied access to the forest by rural communities at whose expense forests are conserved have been found to be no longer tenable. In recent times there has been global recognition of the central role that local communities play in forest conservation and management. Furthermore, it is often neither politically feasible nor ethically justifiable to exclude poor people, who have only limited access to resources from the so-called protected forest areas, without providing them with alternative means of livelihood (Munasinghe and Wells 1992). In Kenya, forests are either gazetted as protected areas and managed as Forest Reserves by the Kenya Forestry Department (FD) or as part of the National Parks system, or they are protected areas for wildlife resources and managed by the Kenya Wildlife Service (KWS). Although these two state agencies complement each other in terms of managing the country's forest and wildlife resources, they are clearly separate and operate under different legislative frame works. Outside of this system of forest protection are forests and woodlands managed by local county councils in areas designated as "Trustlands." Trustlands are a historical concept that bestowed land stewardship on local county councils to hold in trust for the local people. In effect then, trustland forests are "community" forests. While control of forest and wildlife resources within the system of Protected Areas (PA's) could theoretically be enforced by law, this is seldom the case because of the inadequate capacity of the state agencies. Regulation outside the PA's system presents many problems.

This work focuses on the forest ecosystem adjoining the Maasai Mara National Reserve, which forms a critical dispersal area for wildlife populations moving to and from the reserve. Wildlife reliance on dispersal areas can be explained by the fact that no park or reserve is a self-sufficient, all-encompassing ecosystem (Campell *et al.* 1991). Much of the land surrounding the Maasai Mara Game Reserve has traditionally been used by the local pastoral Maasai community for herding cattle, a land-use practice that was compatible with the conservation of forest and wildlife resources. However, in recent years, there has been a progressive shift among most pastoral communities in East Africa, of which the Maasai are prominent, from mainly livestock production to subsistence and commercial modes of crop production. As a consequence of this shift, areas that were previously used as forests and rangelands used by livestock and wildlife are now being cleared for crop production. In the Maasai Mara Reserve, this has led to a reduction in wildlife and livestock habitats around the reserve, which has triggered intense resource competition between wildlife and humans with their livestock.

Lecturer, Department of Forestry, Moi University, P.O. Box 1125, Eldoret, Kenya.

For the forest ecosystems in the Maasai Mara area to continue providing various natural resources for humans and to remain viable dispersal areas for wildlife, the land must remain relatively undeveloped, which represents an opportunity cost to the landowners (Norton-Griffiths and Southey 1995). The goal should then be to identify forest and wildlife resource management options that also generate direct benefits for the local community. This study was designed with this broad objective in mind. This paper presents preliminary findings of a forest resource assessment and attempts to demonstrate that a multidisciplinary approach to forest ecosystem management is most viable in the Mara area.

MATERIALS AND METHODS

The Maasai Mara Game Reserve forms the northern part of the greater Serengeti ecosystem (Sinclair and Norton-Griffiths 1979), in southwestern Kenya, stretching along the Kenya-Tanzania border. The Maasai Mara Game Reserve comprises 1,368 km^2 of relatively low-lying plains (usually < 1,000 m.a.s.l). To the northwestern part of the park in the Transmara District of Kenya is a series of forest blocks (fig. 1) making up approximately 400 km^2 of closed canopy forests, dispersed within 1,700 km^2 of natural rangeland and bush or clustered woodland. The altitude at the Maasai Mara is about 1,500 m.a.s.l. and rises sharply to between 1,600 and 1,950 m.a.s.l. in most of the forested or rangeland areas in the central part of Transmara District. The rainfall regime also ranges considerably from a mean annual rainfall of less than 1,000 mm in the reserve to over 1,800 mm in the higher parts of the district. Because of permanent water sources, wildlife and livestock use the major forest blocks as critical dry season grazing when grass becomes scarce in the open rangelands within and without the reserve.

Forest Sampling

By satellite imagery, major forest blocks were identified in the first stage of the inventory. Selection of forests for sampling was based primarily on size, importance as wildlife habitats, and catchment value. In total, 29 forests were sampled, covering over 100 km^2 (forming one more or less contiguous forest block) in the central Transmara extending to the edge of the Maasai Mara Game Reserve. Aerial photographs taken in 1993 were used to delineate various forest types and formed the basis for determining transects, transect direction, and number of plots per transect. In total, 468 plots distributed among 64 transects were established and surveyed. Plot sizes ranged from 0.02 to 0.08 ha, depending on the density of the forest. Plots were established 100 to 200 m apart depending on the length of the transect and variation within the forest block being sampled. Data collection in each plot consisted of measuring the diameter at breast height (dbh) of all trees in the plot with dbh of > 10 cm, bole height, bole diameter (using a spiegal relascope), and total tree height of four to five randomly selected trees per plot. General site characteristics (drainage, slope, forest floor conditions) were assessed qualitatively. Evidence of forest degradation, such as tree cutting, charcoal burning, debarking, animal trails, and seedling damage, was also recorded. Timber volumes (bole volumes) obviously were crudely estimated following the procedures described in the Wass (1995) report on Kenyan indigenous forests.

Assessing Other Forest Values

In addition to forest assessment, local people were interviewed, engaged in discussions, and asked their views on the following issues:

Forest ownership: Who owns the forest? Communal, group, or private ownership? Is ownership clear?

Forest values: Water catchment: Does the forest have a significant value in terms of water conservation? Are there natural springs or rivers flowing through the forest? Have any changes been observed in streamflow through the area over the years? Socio-cultural values: Are there sacred sites, medicinal plants, ceremonial uses for plants, and wood and nonwood forest products? Are there any watering points and salt licks for animals?

Wildlife habitats: Is the forest frequented by wild animals? Which (migratory, resident, or both) animals? Is the forest a wildlife corridor or source area? Likely destination? Which time of the year are the animals most common in the forest? Damages/problems caused by wildlife? What are the possible intervention measures?

Conservation: Do people support forest and wildlife conservation or are they indifferent to conservation? Who pays and who benefits in forest and wildlife conservation?

Awareness: How aware are the people of the value of the forest and wildlife resources? Is the process participatory? Are people aware of any conservation initiatives?

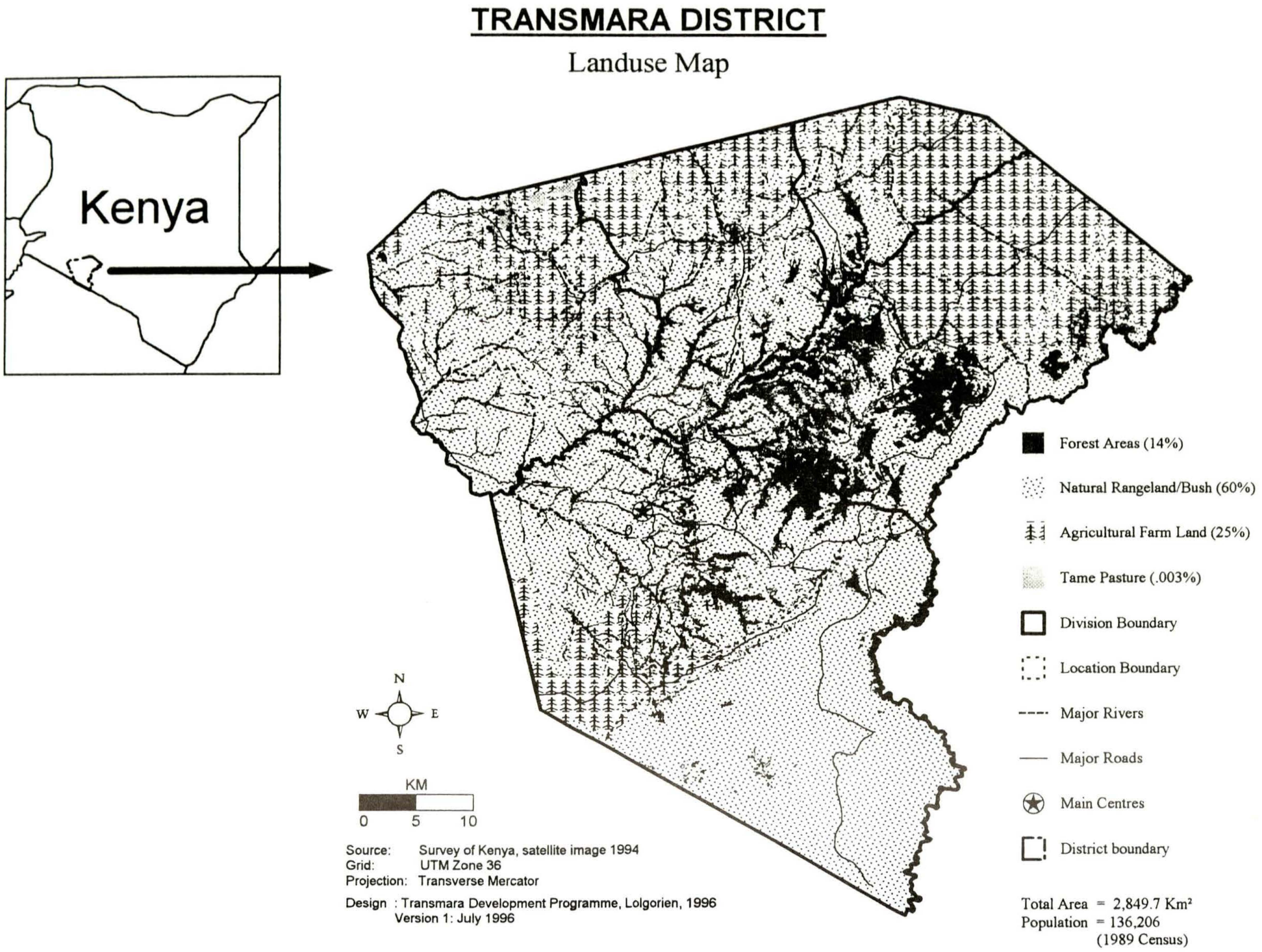
Involvement: How should human-wildlife conflicts be addressed? Compensation question? Role of the local people, state agencies (KWS, FD, bilateral, local, and international conservation non-governmental organizations)?

RESULTS AND DISCUSSION

Forest Characterization in Transmara District

Forest Microtopography

The physical microenvironmental features such as slope, susceptibility to erosion, and drainage are forest specific. Differences observed along a transect are often related to


TRANSMARA DISTRICT
Landuse Map
Kenya
N
W
E
S
KM
0
5
10
■ Forest Areas (14%)
Natural Rangeland/Bush (60%)
Agricultural Farm Land (25%)
Tame Pasture (.003%)
☐ Division Boundary
Location Boundary
---- Major Rivers
— Major Roads
Main Centres
District boundary

Source: Survey of Kenya, satellite image 1994
Grid: UTM Zone 36
Projection: Transverse Mercator

Design : Transmara Development Programme, Lolgorien, 1996
Version 1: July 1996

Total Area = 2,849.7 Km²
Population = 136,206
(1989 Census)

Figure 1.—*Transmara District Land Use Map.*

forest types (species associations). Localized drainage patterns appear to have a significant influence on the growth and distribution of some tree species. In general, most forests in Transmara are found on plains (< 5 percent slope) underlain by poorly drained clay soils. However, differences in topography greatly influence drainage conditions, even within a small area under the same soil type, hence the high diversity of forest types. For example, *Trichocladus ellipticus* is a low canopy shrub that is very prevalent in most parts of the Transmara and usually forms an impenetrable vegetation zone along the forest edge, although the forest floor is virtually bare on poorly drained sites. *Trichocladus ellipticus* has no timber volume but is used for poles, fencing, and fuelwood. In better drained sites, much taller trees and more dense understory vegetation is found. Evidence of erosion was minimal in most forests except along cattle or elephant trails. Most of the forested areas in the district are dissected by a network of perennial and seasonal streams. Any unplanned, wanton destruction of forests, therefore, has the potential to accelerate runoff with an obvious increase in downstream flow and deposition.

Forest Classification and Physiognomy

Forests in Transmara have not been classified but appear to conform to forest classification by White (1983) and Lamprecht (1989). Three main vegetation types were distinguished:

Afro-montane dry conifer: this formation is dominated by *Podocarpus latifolius*. Other important species are *Olea africana*, *Olea capensis*, and *Diospyros abyssinica*. The lower canopy consists of evergreen to deciduous vegetation.

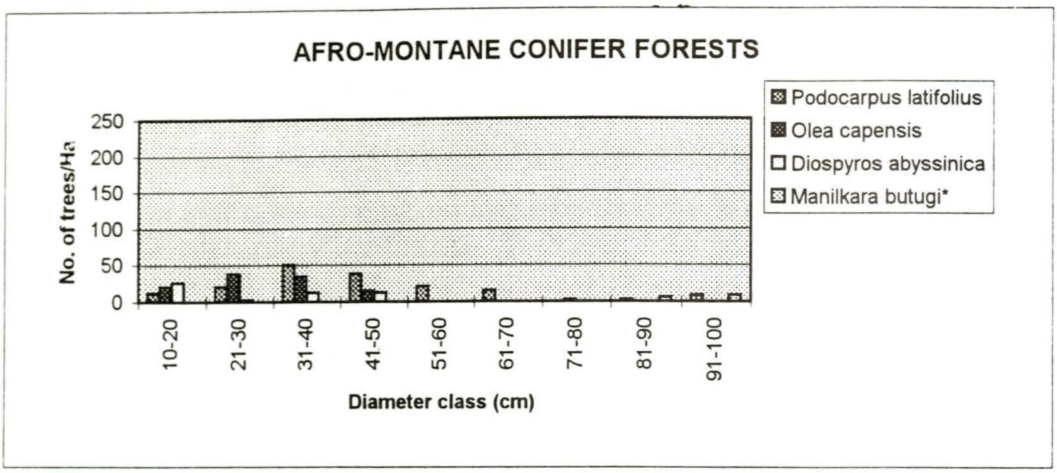
Semi-deciduous (semi-evergreen): this vegetation type occurs in a huge drainage basin forming the single most extensive, contiguous closed canopy forest in central Transmara. The characteristic species are *Olea capensis*, *Diospyros abyssinica*, *Olea africana*, *Warbugia ugandensis,* and *Manilkara butugi*. The lower canopy is comprised of evergreen to semi-deciduous tree species such as *Teclea nobilis*, *Grewia sp*., *Turrea holstii,* and *Trichocladus ellipticus*.

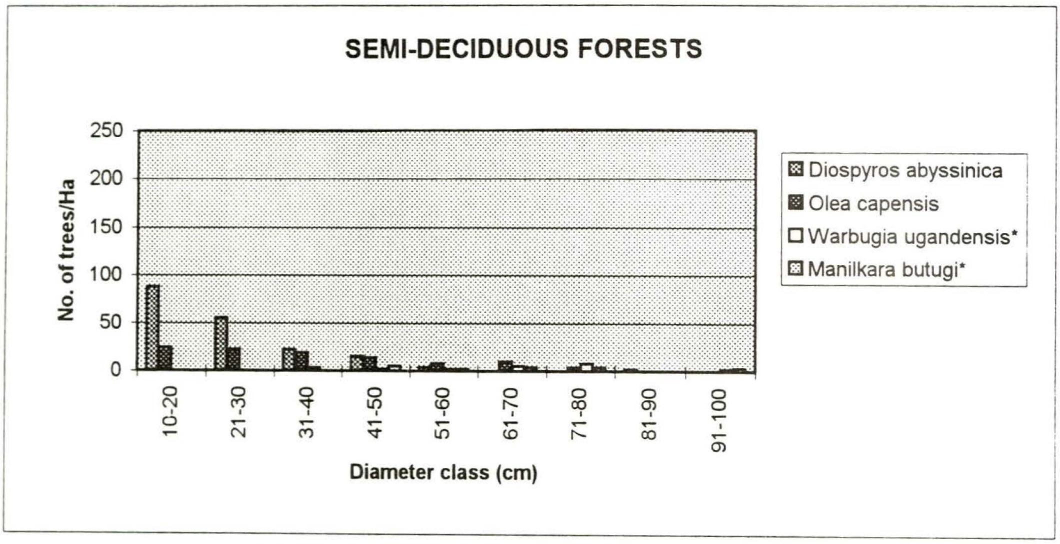
Dry deciduous: this is the most widespread forest type in low rainfall areas (< 1,200 mm) occurring mainly in the transitional zone separating medium altitude (1,000 to 1,600 m.a.s.l.) vegetation from Afro-montane forests. The most abundant species in this formation are *Euclea divinorum* and *Trichocladus ellipticus*. Interspersed within the Euclea/ Trichocladus spp. mixed are other less abundant species such as *Elaeodendron buchananii*, *Manilkara butugi*, *Warbugia ugandensis*, *Olea africana*, *Olea capensis*, and *Diospyros abyssinica*. Infrequent species include *Apodytes dimidiata* and *Pistacia aethiopica*. In addition to these broad classifications of the closed canopy forests, 50 to 60 percent of Transmara consists of open woodland to savanna woodland. The open woodland vegetation has a deciduous tree layer that is rather low in density with mostly separate crowns.

These woodland formations at the landscape level represent a mosaic of "clustered forests." Unlike the savanna woodland that is characterized by scattered trees and grassland, the clustered forest formations can in some cases be as dense and diverse (i.e., species composition) as the closed canopy forest. Conditions within these clustered forests are in most respects similar to the adjacent closed canopy forest. These formations are clearly different from the well-described savanna woodlands. How can this patchwork of "clustered forests" within an open grassland be explained? The frequent use of fire and grazing in these ecosystems has led to random effects of selective burns and subsequently differential vegetation growth. The combined effects of fire and grazing, localized erosion, and deposition (as evidenced by the higher ground level in the clustered forests relative to the surrounding grassland) is a possible explanation. In terms of forest resources assessment, the varying sizes of clusters and random nature of their occurrence present serious sampling difficulties. Yet much of the wood and other forest products of the this entire region in Kenya are found in the clustered forests and should be included in management plans.

In terms of forest structure, the relationship between the number of trees per hectare to diameter class in most of the forest blocks in Transmara generally follows the classical J-inverse shaped curve for most species (fig. 2), except in highly disturbed forests where local exploitation has concentrated on small pole-size classes. Some species, such as *Manilkara butugi* and *Warbugia ugandensis*, were found only in large diameter classes, and species such as *Euclea divinorum* were found in diameter classes below 50 cm. Distributions of individual tree species clearly reflect the successional status of the species, with the light-demanding species such as *Olea capensis* not occurring in lower diameter classes except in forest edges. In terms of vertical forest structure, two categories are distinguished:

1. Low canopy forests with the uppermost canopy layer from 10 to 20 m in height and characterized by one to two layers.
2. High canopy forests with the uppermost canopy layer from 30 to 40 m in height and with at least three layers. Very tall trees (sometime up to 40 m) such as *Diospyros abyssinica* are predominant. Some of these forests are characterized by vertical forest structures typical of those found in tropical rain forests that have multistory canopy layers.





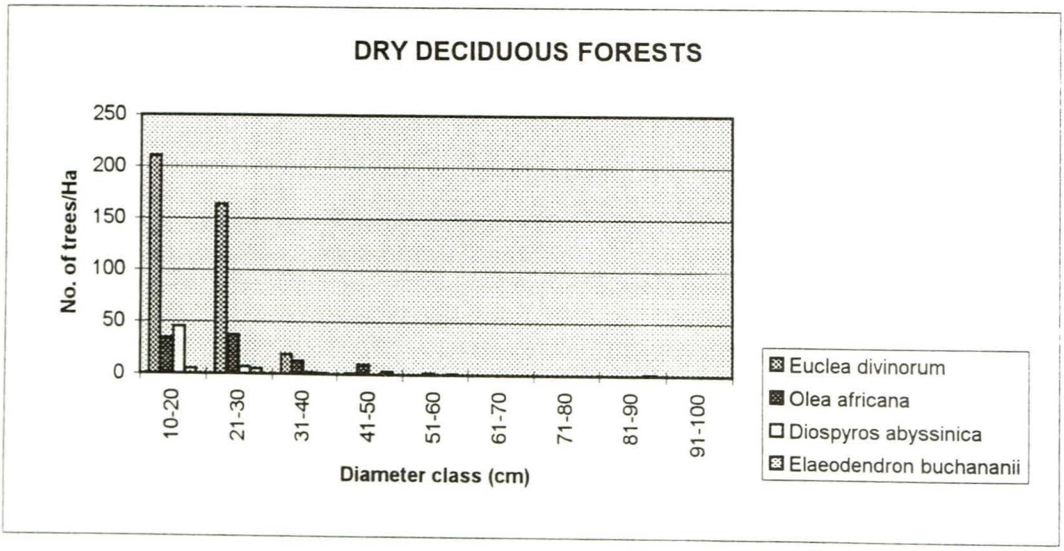


Figure 2.—*Diameter distribution for the most dominant tree species in the three main forest types in Transmara.*

The forests of Transmara are characteristically dominated by a few species (on a unit area basis) forming high "single-species concentrations" of almost pure stands or two- to three-species mixed zones. The dominant species (e.g., those shown in fig. 2) contribute as much as 60 to 70 percent of the overstory vegetation cover. The lack of high tree species diversity in the forests of Transmara is intriguing because the rainfall is high and altitude is similar to other forests in Kenya that have a high tree species diversity. This could be attributed to poor drainage and possibly to impacts of high wildlife (elephants, buffaloes, zebras) and livestock densities. The soils are generally poorly drained. Considerable soil compaction and browsed and trampled tree seedlings were evident in most forest areas.

Commercial Timber Species

The average basal area for all forests sampled in this study is 39.0 m^2 per hectare. Except for recent disturbances and encroachments coming from the forest edges, the remnant forest blocks in Transmara still appear to be in relatively good condition. Bole volume for the tree species in the forests fell between 350 m^3 and 450 m^3 per hectare in the semi-deciduous and Afro-montane dry conifer forests. These volumes are considered high and comparable to well-managed indigenous and plantation forests. Unlike other tropical forests, forests occur in the Transmara in which a single tree species may have more than 50 m^3 per hectare. Species in this category include *Podocarpus latifolius*, *Diospyros abyssinica*, *Olea capensis*, and *Manilkara butugi*. *Warbugia ugandensis* is one of the few dominant species that has high overall volume but is distributed sparsely within the forests. In contrast, *Manilkara butugi* tends to clump together, occasionally resembling an exotic plantation. The overall, average gross merchantable volume of wood in the forests where the commercial species occur in large numbers to be used economically is 137.53 m^3 per hectare; of these, *Diospyros abyssinica* accounts for 25.3 percent of the volume. The proportion of other commercial species is as follows: *Olea capensis*—17.6 percent; *Manilkara butugi*—16.4 percent; *Elaeodendron buchananii*—10.2 percent; *Olea africana*—9.6 percent; and *Warbugia ugandensis*—5.2 percent. *Podocarpus latifolius*, although occurring only in one forest, is in such a high concentration in that forest that it accounts for 24 percent of all the harvestable commercial volume. Commercial timber exploitation is currently non-existent in this region, but the local people are interested in the sustainable use of this resource, hence the need for refining these data. Given the crude volume estimates here and the lack of data on growth rates of virtually all the tree species, timber exploitation at this point is not recommended.

Habitat Diversity

Forests in Transmara are important wildlife sanctuaries and form a crucial dispersal zone for the Maasai Mara National Reserve. The survey revealed numerous wildlife dependent on the forests. Animal movement is both localized as well as migratory within the forest, and to and from the Maasai Mara National Game Reserve. Some of the wildlife populations are residents of the forest, while others, like the elephants, migrate seasonally. The value of the Transmara forests as wildlife habitats comes from variation in site conditions. The diversity of habitats within the forests (riparian forests, open woodlands, open glades within closed canopy forests, old-growth forests, swamps and permanent natural water springs, and salt licks) is reflected in its rich animal diversity. Animals such as elephants are often found in central parts of the forests in dense vegetation. In some areas, understory vegetation dominated by the succulent *Dracina afromontana* evident in several closed canopy forest blocks appears to be maintained by elephants with the consequence that regeneration of tree species is suppressed. During the dry season when pastures and water resources in the low-lying open plains of the Maasai Mara Reserve are scarce, wildlife take refuge in these higher altitude forests and inevitably come into conflict with humans and their domestic animals. The killing of livestock and damage to crops by wildlife are common in the area, and the lack of a compensation system makes conservation difficult to sell to the local people.

Wildlife can have both positive and negative impacts on forest structure and on the overall integrity of the forest ecosystem. The two main influences relate to actual physical damage to trees and other vegetation and to forest floor-soil compaction through trampling, both of which affect tree regeneration. Tree regeneration was generally low in most forest blocks in the district, which could be attributed in part to high animal populations (both wild and domestic). In all forests frequented by wildlife, over 40 percent of the area sampled showed evidence of damage in the form of soil compaction, numerous animal trails, trampled seedlings or saplings, and trees felled by elephants (or broken branches).

Anthropogenic Forest Influences

Forest Disturbance

The main human threats to the forests include cultivation, forest clearing for settlement, tree felling for charcoal production, cutting of building poles, overgrazing, and medicinal extraction. Cultivation is done either by the Maasai landowners or by cultivators from other parts of the country who lease the land. The drive to cultivate in the traditional pastoral Maasai is a socioeconomic issue that has direct consequences on the conservation of forests and wildlife in much of Kenya. Charcoal production has increased in the area because of the existence of large urban markets elsewhere in the country and because Transmara is one of the few remaining parts of Kenya endowed with rich wood resources. Building of houses and construction of fences by individual farmers following the subdivision of land from a traditionally communal form of ownership to private ownership have exerted much pressure on forests in the form of cutting of pole-size trees. Another consequence of land subdivision is the people's desire to own and settle on their own piece of land, leading to forest clearings for settlement, and at the landscape level, habitat fragmentation. Reduced land area arising from the a forementioned uses has led to overgrazing, and this problem is expected to increase unless management interventions are put in place. Invasion of rangelands by *Acacia gerrardii* forming virtually impenetrable thorn thickets and the prevalence of low quality "wire grass" *(Pennisetum hohenackeri)* in most of the Transmara area are clear indicators of poor rangeland conditions caused by mismanagement. Bark extraction from some tree species (e.g., *Olea capensis)* for traditional bee hives and from *Warbugia ugandensis* for medicinal purposes has led to high tree mortality. When an dominant overstory species like *Olea capensis* dies, huge forest gaps are created, which in most cases leads to invasion of weed species that alter the forest composition and structure.

Sociocultural and Other Forest Values

Over 95 percent of the people interviewed expressed high appreciation of the role of trees in their culture and the need to conserve the forests. Trees are widely used for treating ailments, in warding off dangers, and as final arbiters in the settlement of human disputes. Interactions with local people in the course of this study revealed a considerable level of sociocultural, and socioeconomic value attached to the forest. The subsistence economy of the communities living in or adjacent to the forest depends directly or indirectly on the forest. The preponderance of relatively undeveloped rangeland in Maasailand is evidence of a conservation-oriented culture that has had elaborate traditional land-use systems. Traditional medicine is not only of local value, but also is now being recognized and patronized by governments in many parts of the world. The screening of medicinal plants is carried out by specialized institutions (Baquar 1995). There is, therefore, a valid case in exploiting indigenous plant knowledge of medicine and promoting land-use practices that are compatible with the conservation of forests. There is considerable potential for commercial medicinal plant extraction in Transmara forests to benefit the local community.

The local people's attitude to forest conservation is overwhelmingly positive. However, the presence of large populations of wildlife and associated conflicts has significantly changed this attitude in recent years. Among the individuals interviewed, only 8 percent favored forests and wildlife conservation under existing conditions, while 73 percent favor conservation of forests if they do not harbor wildlife. Eighty-eight percent would support wildlife conservation if animals are confined to the PA system or if there is adequate compensation for damages caused by wildlife. In conclusion, unless adequate benefits are derived from the Transmara forests, the fact that they are *habitats* for wildlife threatens their existence and that of wildlife itself as people seek to clear forests to chase animals away.

Forest Management Implications

Several important management considerations and further research questions come out of this study. Firstly, it is clear that the Transmara forests have remained relatively intact for a long time, largely as a result of the pastoral system of land use by the local community whose culture is compatible with conservation. The major form of forest exploitation is a subsistence economy with minimal impact on the forest. However, recent shifts in the pastoral lifestyle toward crop production put a premium on forest land. Will commercial forestry lend itself as a competitive land-use alternative in this district and are the indigenous hardwoods a sustainable resource? Transmara contains some valuable wood resources, but the forests form a crucial habitat for wildlife. Wildlife is perhaps of more national importance than commercial forestry. Research on logging generally shows selective logging operations that involve the removal of only a few trees per hectare, which obviously has less impact than complete clearing and may even be beneficial. There is currently no mechanized timber industry in Transmara. Species such *Olea capensis*, *Olea africana*, and *Warbugia ugandensis* are in some instances converted into less valuable uses such as charcoal production when they could fetch much more money as timber.

Although the forest assessment has revealed a considerable raw material base to support some wood industry, data are not available on tree growth rates, harvesting methods, logging costs, and the sustainability of indigenous timber exploitation vis a vis other land-use options. A central objective for the multiple exploitation of forests is to determine which products can be removed, which harvesting techniques to use, and what level of exploitation can ensure sustainability. This principle must, however, be well understood by all the forest users; the situation can become very complicated where the main beneficiaries of a particular forest product are not the inhabitants of the area.

There is the question of wildlife as a natural resource and heritage. Current legislation prohibits game hunting in Kenya. There is a marked increase in human-wildlife conflict in Transmara. Conflict is intense when agriculture is involved, particularly where cropland borders forested areas and where pockets of agriculture are surround by rangelands. Conflicts arise because wildlife destroy property and may injure or even kill humans and domestic animals. During this study, baboons and vervet monkeys were the most notorious crop raiders while elephants were the most destructive and problematic wildlife species. This is the major problem facing the communities living in the Transmara area where wildlife conservation is practiced. For years, the Maasai have coexisted with wildlife, and there is ample historical evidence to show that present human-wildlife conflicts in much of Maasailand can be traced back to inappropriate policy decisions as well as to the exploitative tourist industry in Kenya that until recently totally disregarded the rights of local people at whose expense wildlife is conserved. In the Transmara area, for example, forests have remained important wildlife habitats because for many years landowners simply did not bother about their economic value. People now understand the economic value of land and wildlife and are set on exploiting it to its full potential. Norton-Griffiths and Southey (1995) present an interesting economic analysis that clearly shows that for the Maasai landowner:

$$\text{Net Revenue}_{(\text{agriculture})} >>> \text{Net Revenue}_{(\text{from livestock})} >> \text{NR}_{(\text{from Conservation})}$$

The additional costs to conserve natural resources over and above the costs local people are willing to bear, because of direct and intrinsic values they derive from use of the resources, must be the responsibility of both the national government and the larger international community. There is no point extolling the virtues of conservation without a fair consideration of the conservation costs. Ecotourism has been suggested as one mechanism through which local people can reap benefits from wildlife. As an option, it has a great potential given the beautiful scenery and large wildlife populations in the district, but this is a fragile industry dependent on external factors that are beyond not only the control of local communities, but also the national government. To what extent should local people be involved in tourism or ecotourism as a means of reaping direct benefits that accrue from wildlife conservation? What local institutional mechanisms exist for cost and benefit sharing, if and when such revenues accrue? What are the vital wildlife dispersal areas and how can human-wildlife conflicts be minimized in the Transmara?

The solution to forest and wildlife resource management appears multifaceted. Forests, wildlife, and humans are inextricably linked in Transmara. A conservation strategy will inevitably need to address the different levels of these interactions. The conservation argument must be presented in terms of the full range of benefits (controlled level of forest product exploitation—timber and non-timber forest products, sociocultural and service functions, ecotourism) within a well-elaborated management plan derived from multiple-level land-use planning. For this to happen, a well-defined institutional framework is required in which identifiable and democratic local community institutions exist with necessary technical backing from government agencies such as KWS and FD, and support of international conservation agencies. The question of institutional collaboration (KWS, FD, local community institutions, and concerned conservation agencies) in natural resource management is very important. Many forest and wildlife conservation initiatives have failed more as a result of institutional impediments than for technical reasons.

From a forest resource assessment and monitoring standpoint, two significant conclusions can be drawn. First, that the current emphasis on multiple use and forest management represents a major shift in conventional forest assessment practice and presents greater research challenges in terms of forest assessment tools. It also requires an interdisciplinary approach. Secondly, due to a diversity of land tenure regimes, especially in sub-Saharan Africa, there is a need to recognize the broad spectrum of forest resource use patterns within and beyond PA's and involve local landowners in resource assessment, management planning, and resource use monitoring.

ACKNOWLEDGMENTS

I thank the German Technical Agency (GTZ) and the Government of Kenya Transmara Development Programme for their financial support that made this study possible. I also gratefully acknowledge the support given to enable me to present this paper at the Second International Symposium on Integrated Tools for Natural Resources Inventories in the 21st Century, Boise, Idaho, USA, August 16-20, by the UK-Department for International Development (DFID), Moi University, and symposium organizers.

The following people reviewed this manuscript: Wayne T. Vos, School for Field Studies, Centre for Wildlife Management Studies, P.O. Box 47272, Nairobi, Kenya; and Donald O. Ogweno, Department of Forestry, Moi University, P.O. Box 1125, Eldoret, Kenya.

LITERATURE CITED

Baquar, S.R. 1995. The role of traditional medicine in rural environment. Nairobi, Kenya: East Africa Education Publishers Ltd..

Campell, K.I.I.; Huishi, S.A.; Kajuni,. A.R., eds. 1991. Serengeti National Park Management Plan for (1991-1995), Arusha, Tanzania National Parks. Dar es Salaam.

Lamprecht, H. 1989. Silviculture in the tropics: tropical forest ecosystem and their tree species - possibilities and methods for the long term utilization. Eschborn.

Munasinghe, M.; Wells, M. 1992. Protection of natural habitats and sustainable development of local communities. In: Cleaver, K.; Munasinghe, M.; Dyson, M.; Egli, N.; Peuker, A.; Wencelius, F., eds. Conservation of west and central Africa rainforests. World Bank Environ. Pap. 1. 353 p.

Norton-Griffiths, M.; Southey, C. 1995. The opportunity costs of biodiversity conservation in Kenya. Ecological Economics. 12: 125-139.

Sinclair, A.R.E.; Norton-Griffiths, M., eds. 1979. Serengeti: dynamics of an ecosystem. Chicago: Chicago University Press. 389 p.

Wass, P., ed. 1995. Kenya's indigenous forests: status, management and conservation. IUCN, Gland, Switzerland and Cambridge, UK. 205 p.

Integrated Permanent Plot and Aerial Monitoring for the Spruce Budworm Decision Support System

David A. MacLean

Abstract.—Spruce budworm (*Choristoneura fumiferana* Clem.) outbreaks cause severe mortality and growth loss of spruce and fir forest over much of eastern North America. The Spruce Budworm Decision Support System (DSS) links prediction and interpretation models to the ARC/INFO GIS, under an ArcView graphical user interface. It helps forest managers predict budworm outbreak effects on forest structure and productivity, forecast forest growing stock and sustainable harvest levels, optimize protection (biological insecticide use) programs, and use silviculture and harvest scheduling to restructure forests to reduce future damage. The Spruce Budworm DSS has been operationally implemented on 8 million ha of susceptible forest in the province of New Brunswick, and is being implemented on test landbases in Quebec, Ontario, and Alberta. The use of inventory and monitoring data in the DSS will be described in four areas: stand growth model calibration, model validation, pest monitoring, and forest stratification for calculating marginal timber supply benefits.

Spruce budworm (*Choristoneura fumiferana* Clem.) is the most destructive forest pest in Canada, causing about 40 percent of the 81 to 107 million m^3 timber volume loss to insects and disease each year (Sterner and Davidson 1982, Power 1991). Sustainable harvest (long-run sustained yield) and current harvest levels for Canada are about 240 and 180 million m^3/year, respectively (Rotherham 1991), only roughly twice the volume lost to pests. Clearly, timber supply can be substantially improved if losses to pests can be reduced (MacLean 1990). This has prompted development of the Spruce Budworm Decision Support System (DSS), which uses models, GIS, inventory data, and pest data to assist in insect and forest management decisionmaking (MacLean and Porter 1994, 1995; MacLean *et al.* 1997).

Major budworm outbreaks have occurred over much of eastern North America three times in the 20th century, causing large-scale mortality of host balsam fir (*Abies balsamea* (L.) Mill.) and spruce (*Picea* sp.) (Blais 1983). Spruce budworm is a native insect that feeds on the current-year foliage, reducing growth and eventually causing up to 85 percent mortality in fir and 35 percent mortality in spruce stands (MacLean 1980). Budworm outbreaks typically last about 10 years, and play a role in "recycling" mature or overmature spruce-fir forest to younger age classes, often resulting in a cyclical succession pattern of fir replacing fir. However, budworm outbreaks also kill forest over large areas, reduce timber supply, increase fire risk, and affect most consumptive and nonconsumptive values (MacLean 1990).

The Spruce Budworm DSS links a suite of prediction and interpretation models to the ARC/INFO GIS, under an ArcView graphical user interface (MacLean and Porter 1994, 1995). It assists forest managers in predicting outbreak effects on forest structure and productivity, forecasting forest growing stock and sustainable harvest levels, optimizing protection (biological insecticide use) programs, and using silviculture and harvest scheduling to restructure forests to reduce future damage. The Spruce Budworm DSS has been operationally implemented on 8 million ha of susceptible forest in the province of New Brunswick, and is being implemented on test landbases in Quebec, Ontario, and Alberta. DSS components include a defoliation-based stand growth model (MacLean 1996), a forest inventory projection system that predicts spatial effects of future budworm outbreaks (MacLean and Porter 1996), and a system for planning spray programs based on marginal timber supply benefits (MacLean and Porter 1995, MacLean *et al.* 1997).

In this paper, I will describe the Spruce Budworm DSS and discuss use of forest inventory and monitoring data by the DSS in four areas:

1. **model calibration**, whereby 135 research permanent sample plots (PSP's) have been measured annually since 1985 for defoliation and tree mortality, measured every 3 years for growth, and assessed for a wide variety of site and stand characteristics;
2. **model validation**, for which an independent network of 2,400 PSP's were measured every 3 to 5 years for growth and yield assessment and insect damage by forest industry and the New Brunswick provincial government;
3. **pest damage monitoring**, in which population sampling and aerial surveys are conducted each year

---

Project Leader, Forest Management Systems, Canadian Forest Service – Atlantic, Natural Resources Canada, P.O. Box 4000, Fredericton, NB, E3B 5P7 Canada.

over the entire forest of New Brunswick, to provide input to the DSS and insecticide protection programs; and

4. **forest stratification for projections**, in which photo-interpreted stand-level species, age, and crown closure are used to determine development classes for timber supply projections and to calculate marginal timber supply benefits of budworm management.

THE SPRUCE BUDWORM DSS

The Spruce Budworm DSS can be used to determine effects of budworm outbreaks and alternative forest management regimes on timber supply, sustainable harvest levels, and forest structure (MacLean 1998). The primary means of reducing losses from budworm outbreaks are altering forest structure through silviculture (planting, thinning), scheduling harvest to preempt or "capture" mortality, or directly preventing defoliation by insecticide use. The DSS is typically implemented on a forest management unit basis because it uses existing growth and yield projections and harvest schedules for the landbase in estimating effects of budworm outbreaks. The Spruce Budworm DSS graphical user interface (GUI) was originally programmed using the Arc Macro Language (AML) (MacLean and Porter 1995), but ArcView 3.0a now provides a much easier means of attaining GUI functionality.

Rather than real-time prediction of future budworm outbreaks, the Spruce Budworm DSS uses a scenario planning approach to examine "what if" outcomes of user-specified scenarios. Budworm scenarios typically include altering the temporal sequence of defoliation that makes up an outbreak, the timing of when an outbreak begins (e.g., "what if" an outbreak began in the year 1998, 2000, or 2005?), and the length of the outbreak. Scenario planning is a disciplined method for imagining possible futures, which has been applied to a wide range of issues (Schoemaker 1995). Among the many tools a manager can use for strategic planning, scenario planning is unique for its ability to capture a whole range of possibilities, thereby allowing managers to see a wider range of possible futures (Schoemaker 1995).

Spruce Budworm DSS Inventory Projection System

The Spruce Budworm DSS Inventory Projection System (IPS) allows users to "grow" their forest inventory up to 30 years in the future, incorporating the effects of two severities of budworm outbreaks, decisions about whether or not to use insecticides during the outbreak, as well as other management options (MacLean and Porter 1996). IPS allows a manager to visualize future forest conditions by simulating stand development, spruce budworm outbreaks, and forest protection. IPS uses a GIS-based spatial forest inventory, volume yield curves, and management plan information to project the forest. Its key capability is accounting for the effects of spruce budworm outbreaks and the effects of forest protection to combat budworm defoliation. The timing and nature of these events are controlled by the user on a scenario basis. The system can be used to update old (e.g., 1990) inventory data to the present, using actual past (1990-1998) defoliation data for that landbase from aerial surveys, or to conduct "what if" explorations of the results of combinations of outbreak timing, severity, and protection on future forest structure. Visualization of forecast results is possible through a combination of thematic maps, bar charts, and tables. IPS consists of software modules developed using the C programming language, ARC/INFO's AML, and ArcView's Avenue language, and has been implemented both on a Sun workstation platform and on a PC (MacLean and Porter 1996).

Conducting an IPS projection requires that the user specify the year to project to, the base year of the inventory, the timing of occurrence and severity of a budworm outbreak, and whether protection will be applied during the outbreak (MacLean and Porter 1996). Protection is assumed to limit defoliation to < 40 percent of current foliage each year, prevent budworm-caused mortality, and maintain stand volume development at management plan levels. One can project each ownership on the landbase separately or all together. Management planning procedures in New Brunswick assemble stands into classes based on species, stand age, site productivity, or other criteria. Each of these classes is linked to a set of volume-based yield curves (one curve for each species), and during a projection, each stand is tracked along the appropriate set of curves. When a budworm outbreak occurs, IPS modifies the balsam fir and spruce yield curves by budworm impact vectors to simulate the results of budworm defoliation reducing tree growth rates and increasing mortality. These impacts depend upon the species, stand maturity, outbreak severity (moderate or severe), and protection options selected by the user and are classified into four species mixes: balsam fir, fir-hardwood, spruce, and spruce-hardwood (MacLean and Porter 1996).

Spruce Budworm DSS Protection Planning System

The Spruce Budworm DSS Protection Planning System (PROPS) quantifies the marginal timber supply benefits of protecting stands against budworm defoliation (fig. 1), with the calculation made at the scheduled time of harvest (MacLean *et al.* 1997). It allows the user to determine the effects of different budworm protection strategies, using the biological insecticide *Bacillus thuringiensis* (*B.t.*), on forest development and sustainability, and it quantifies the relative volume benefit of alternative spray blocks.

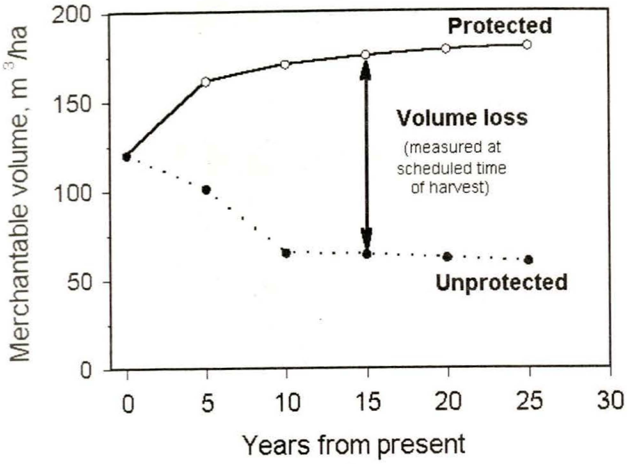


Figure 1.—*The concept underlying the Spruce Budworm DSS Protection Planning System (PROPS). Volume projections are made for each class of stands using the model STAMAN, for protected (sprayed with the insecticide* B.t. *to limit defoliation to < 40 percent of current foliage each year) and unprotected budworm outbreak scenarios. Then volume loss (protected minus unprotected) is calculated, at the scheduled time of harvest for individual stands, and mapped as the protection priority (m^3/ha) for each stand. This example shows volume development for 30 years in an immature balsam fir-spruce stand, with a 10-year budworm outbreak starting in year 0.*

MacLean *et al.* (1997) described the implementation of PROPS on a 188,000-ha landbase in northern New Brunswick, Canada. Implementation involved constructing databases that specified future volume reductions for all stand types and all possible levels of defoliation over the next 10 years (1996-2005). PROPS then predicts the marginal timber supply (m^3/ha) benefits, at the scheduled time of harvest, of protecting stands against spruce budworm defoliation in a given year (fig. 2). MacLean *et al.* (1997) conducted a series of strategic planning analyses of the consequences of different future budworm outbreak and protection scenarios on future growing stock and harvest levels. This involved evaluating: (1) different future budworm outbreak scenarios, with and without protection; (2) effects of budworm spraying not meeting foliage protection targets; and (3) effects of part of the landbase not being protected. Analyses demonstrated that period 4 (2010-2015) harvest levels, and to a lesser extent, period 3 (2005-2010) levels, were very sensitive to any reduction in yields caused by defoliation. This was because in period 4, harvest levels nearly equaled operable growing stock. If protection was applied but defoliation exceeded the foliage protection target (limit defoliation to < 40 percent of current foliage) by 20, 30, or 40 percent on 20 percent of the landbase, period 4 harvest level reductions of 110,000, 290,000, and 590,000 m^3, respectively, would be necessary to maintain sustainability. If only 20 percent of the landbase failed to reach protection targets under severe outbreak conditions, then period 4 harvest would have to be reduced by 590,000 to 930,000 m^3 (MacLean *et al.* 1997).

There was wide variation in the marginal timber supply benefits of protection. For example, one scenario, specifying that a budworm outbreak began in 1996, projected that protecting 50,000 ha of the highest priority stands, at a cost of $1,000,000 Cdn. would give a payback of 1,980,000 m^3 of timber at the scheduled time of harvest, but protecting the same area of lower priority stands would return only 480,000 m^3. It was concluded that the only way planned harvest levels for the test landbase could be maintained under severe spruce budworm outbreak conditions was with an aggressive protection policy. For this landbase and management regime, protection against spruce budworm clearly pays (MacLean *et al.* 1997).

PROPS also assists users in planning insecticide spray operations against spruce budworm. The Xtools ArcView Extension[1] was used to build functions to easily add a spray block theme, draw spray blocks, intersect these with a protection priority (volume loss) theme, and display charts of mean volume (m^3/ha) benefit per spray block and tabular output of block area and total volume benefit. The ArcView Dialog Designer Extension[2] was used to design the toolbar, custom interface, and dialog boxes. Functions are packaged in a Spray Tool toolbar, and include buffering capability to determine spray exclusion areas around water bodies, human habitation, or other non-spray areas. Although chemical insecticides have been used in the past for budworm spraying, only the biological insecticide *B.t.* is used now.

USE OF INVENTORY AND MONITORING DATA IN THE SPRUCE BUDWORM DSS

The Spruce Budworm DSS uses forest inventory and monitoring data for initialization of both forest structure and pest incidence over the last 5 years. Both IPS and PROPS use GIS-based, photo-interpreted inventory data on species composition, age class, and crown closure (a surrogate for stand density) as the basis for projections. PROPS also overlays defoliation data, from annual aerial

---

[1] *Developed by Mike DeLaune, Oregon Department of Forestry, 1998. The Xtools ArcView Extension can be downloaded from http://www.odf.state.or.us/sfgis.*

[2] *Developed by Environmental Systems Research Institute, Inc. (ESRI), Redlands, CA. Available for download at http://www.esri.com/software/arcview/extensions/dialog.*

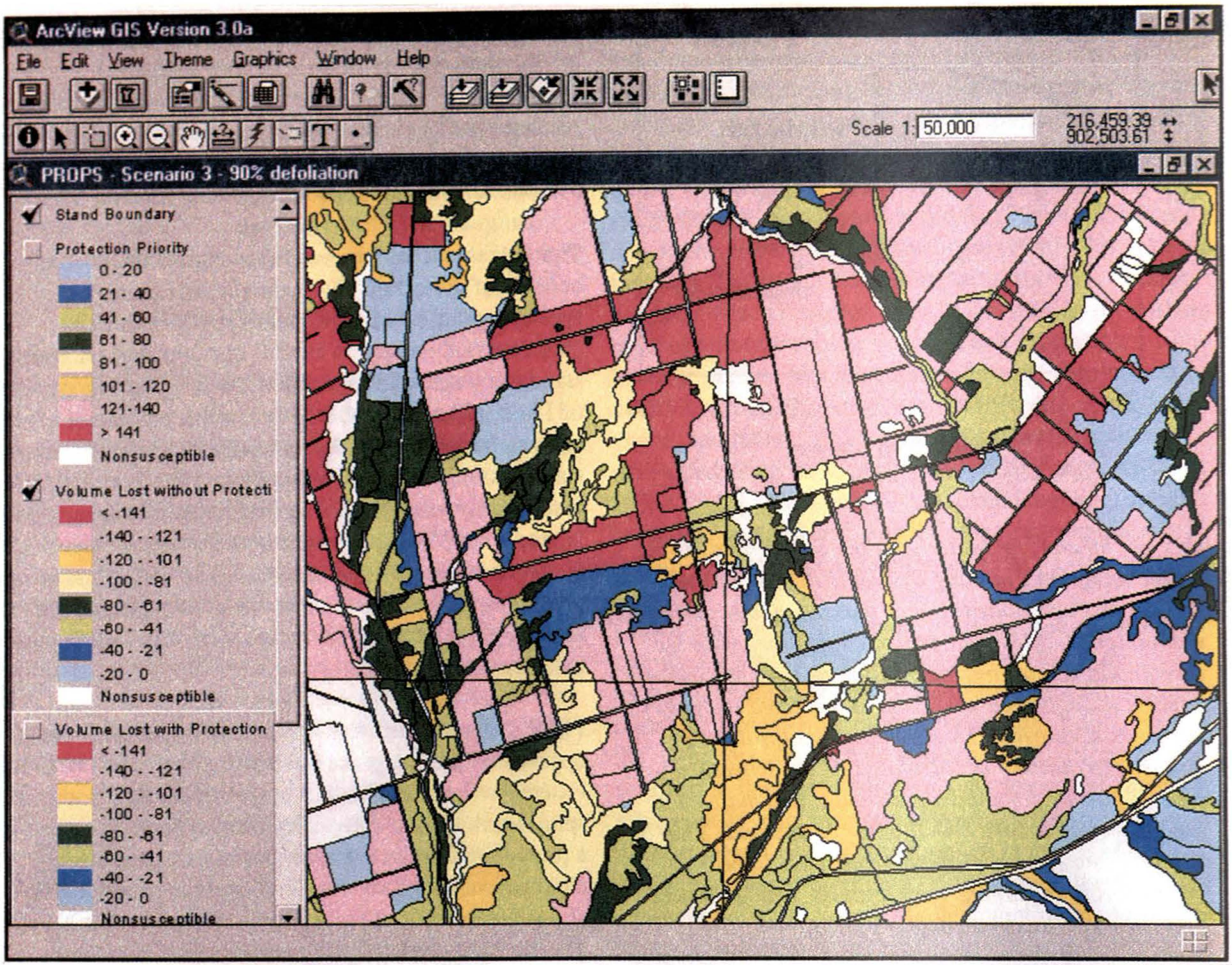

ArcView GIS Version 3.0a
File Edit View Theme Graphics Window Help
Scale 1: 50,000
216,459.39
902,503.61
PROPS - Scenario 3 - 90% defoliation
Stand Boundary
Protection Priority
0 - 20
21 - 40
41 - 60
61 - 80
81 - 100
101 - 120
121-140
> 141
Nonsusceptible
Volume Lost without Protecti
< -141
-140 - -121
-120 - -101
-100 - -81
-80 - -61
-60 - -41
-40 - -21
-20 - 0
Nonsusceptible
Volume Lost with Protection
< -141
-140 - -121
-120 - -101
-100 - -81
-80 - -61
-60 - -41
-40 - -21
-20 - 0
Nonsusceptible

Figure 2.—*Spruce Budworm DSS Protection Planning System (PROPS) viewed in ArcView 3.0. The theme displayed is volume loss caused by spruce budworm defoliation, without insecticide protection, under a scenario of 90 percent current defoliation each year for 10 years. Scale is 1:50,000; stands are for a landbase in northern New Brunswick, Canada. Other themes that can be displayed include volume loss with protection and protection priority, defined as the m*^{3}*/ha difference between projections with and without protection.*

sketch-map surveys for the last 5 years, on forest inventory data to assign defoliation to stand polygons. Past defoliation is used to initialize the current condition of stands in PROPS.

In addition to these obvious uses, the Spruce Budworm DSS has made use of or has influenced inventory and monitoring data in four areas: model calibration, model validation, pest damage monitoring, and forest stratification for projections. Each of these will be discussed in the following sections.

Model Calibration

The STAMAN stand model is an integral component of the Spruce Budworm DSS, and is used to quantify the stand-level effects of budworm outbreaks (MacLean 1996). STAMAN is a simulation-based stand table projection model that calculates periodic (5-year) increment and survival for tree classes defined by species, dbh, and age, to project overall stand development over time (Vanguard Forest Management Services Ltd. 1993). STAMAN is programmed in FORTRAN, and both UNIX and DOS versions are available. A conventional stand table format is used to define the structure of a stand at any point in time, with each species described as cohorts of trees, aggregated by size (dbh) and age. Stand development is determined by the rates of growth of single trees, survival, and recruitment of new stems (i.e., ingrowth). Relationships are calibrated using plot data. STAMAN is used by forest industry in New Brunswick to determine stand volume yields for forest management planning.

STAMAN was modified and calibrated to allow it to predict effects of spruce budworm defoliation on stand development (Vanguard Forest Management Services Ltd.

1993). This involved adding functions to optionally modify growth and mortality relationships to account for damage from pests. Defoliation effects were incorporated into STAMAN as incremental impacts that reduced tree growth and increased mortality. This approach required the definition of functional relationships that predict growth and survival independent of defoliation effects, as well as relationships between the severity of defoliation and the resulting levels of growth loss and mortality; then, the user specifies defoliation levels over time. A network of 135 spruce and fir research PSP's has been measured annually since 1985 for defoliation and tree mortality, measured every 3 years for growth, and assessed for a wide variety of site and stand characteristics (MacLean and Erdle 1986, MacLean and MacKinnon 1997). Details of plot selection criteria, establishment, and measurement methods were presented by MacLean and Erdle (1986). Each stand was sampled with three variable-radius (prism) plots (basal area factor 2.0 m^2/ha) located 120 m apart. Trees were permanently numbered, identified by species and crown class, and measured for standard mensurational characteristics. This data set was used to define and calibrate budworm impact relationships for STAMAN (Vanguard Forest Management Services Ltd. 1993, Erdle and MacLean unpublished). Screening of a number of tree and stand variables, as well as defoliation, indicated that incremental growth reduction was related only to defoliation, but that survival reduction was a function of defoliation, tree species, and stand age (Erdle and MacLean unpublished).

Spruce budworm is one of few insect pests for which stand dynamics models and extensive, detailed impact data are available. Most other pest DSS, either currently available or under development, deal solely with qualitative estimation of risk or vulnerability. More effort needs to be focused on quantification and the development of models that predict effects of a variety of insect pests and other disturbances on stand dynamics. Such models are necessary for accurate, sustainable resource management planning. PSP measurements that include defoliation and pest data are the best source for calibrating impact relationships.

Model Validation

Validation and refinement of stand volume predictions should be ongoing, given the importance of yield prediction in determining sustainable harvest levels and planning future forest structure. Assessment of uncertainty of yield predictions, and research and monitoring designed to reduce uncertainty, are inherent to adaptive management of forests. Management planning in most jurisdictions is an iterative process, whereby plans are periodically revised, timber supply and annual allowable cut (AAC) are recalculated, and changes to the forest landbase are updated. In New Brunswick, 5-year operating and 25-year management plans required under provincial legislation are revised every 5 years. These plans must include 80-year projections of timber supply. Each iteration, or revision of management plans, should be seen as a "window of opportunity" to revise models and recalibrate relationships to improve or validate projections.

In New Brunswick, the STAMAN model has been used to develop volume yield curves for each forest class, generally comprised of species, age, density, and silvicultural treatment groupings. In 1987, a cooperative PSP measurement program was begun, whereby forest industry and the New Brunswick Department of Natural Resources and Energy (NBDNRE) established a network of over 2,400 PSP's, specifically for use in calibrating or validating stand growth models. These fixed-area plots with permanently numbered trees are measured every 3 to 5 years (depending upon age class) for a wide range of mensurational characteristics including dbh, height, crown dimensions, ingrowth, mortality, and cause of mortality. Because of the importance of spruce budworm defoliation in New Brunswick, each tree in the plots is also assessed for current-year and cumulative (all age classes of foliage) defoliation, in 20 percent classes. This ongoing monitoring of indicators of stand development, designed for validation and reduction of uncertainty, is a critical component for improving management planning. Although insect damage assessment is not the primary reason for the plot network, it is significant that defoliation is being assessed as one of the variables influencing stand development.

Pest Damage Monitoring

Each year, NBDNRE conducts two spruce budworm surveys to determine expected population levels for the upcoming year and to assess levels of damage that have occurred; monitoring data from both surveys are annually updated and used in the Spruce Budworm DSS. These surveys use methods that have been refined over many years (Dorais and Kettela 1982) and are similar in most provinces in eastern Canada. The population survey involves collecting midcrown branch samples at up to 2,000 sample points across the province, determining the number of second-instar (overwintering stage) spruce budworm larvae present, and using this in projecting expected defoliation levels in the upcoming year.

A separate aerial sketch map survey is used to estimate current-year defoliation each year (Carter and Lavigne 1993). These annual surveys are conducted to provide extensive overviews of the distribution and severity of budworm feeding throughout the province, for use in designing protection programs. Because they are the only source of defoliation data over large forest areas, they have also been used in the Spruce Budworm DSS. Trained, experienced observers in Cessna 172-type aircraft (at an altitude of 150 to 300 m) systematically fly east-west flight lines approximately 2 to 5 km apart over known budworm infestation zones. Since 1991, aircraft used in the survey have been equipped with Loran C navigation systems to improve the accuracy of mapping. Aerial assessments are conducted during a 1- to 2-week period, immediately following the completion of spruce budworm feeding. At this time, a distinct reddish-brown coloration of dry foliage appears, due to budworm severing and webbing together needles in the process of feeding. Areas with noticeable reddish-brown coloration of foliage are recorded on 1:190,000 scale (1 inch = 3 mile) maps in three defoliation classes: light (11-30 percent), moderate (31-70 percent), and severe (71-100 percent) (Carter and Lavigne 1993). Areas with no noticeable defoliation are assigned to a nil (0-10 percent) class.

To assess possible use in DSS, MacLean and MacKinnon (1996) evaluated the accuracy of aerial sketch mapping estimates of spruce budworm defoliation from 1984 to 1993 in 222 to 325 sample plots in spruce-fir stands in New Brunswick. Aerial defoliation estimates were compared with ground-based binocular estimates of current defoliation for an average of 10 trees/plot (range 5-20). Overall, 56 percent of plots were correctly rated by aerial sketch-mapping in four classes (nil, light, moderate, and severe), with 37 percent of the plots underestimated and 7 percent overestimated. The predominant error (26 percent of plots) was rating defoliation as nil (0-10 percent) from the air when it was actually light (11-30 percent). This error was deemed not important in terms of predicting tree response, since data from the literature indicated that defoliation less than 30 percent did not cause tree mortality, although if continued, it would reduce growth. Using three defoliation classes (by combining nil-light, 0-30 percent), 82 percent of the plots were correctly classified by aerial sketch mapping. MacLean and MacKinnon (1996) concluded that aerial sketch mapping of spruce budworm defoliation is a viable technique that can be used for both surveys and DSS that estimate forest response to budworm outbreaks and management activities.

Forest Stratification for Projections

Forest management planning and timber supply analyses generally involve assembling stands into classes based on tree species, age, site productivity, density, silvicultural treatment, or other criteria. Each of these classes is linked to a set of volume-based yield curves (either a cumulative volume over age curve or species-specific curves within each class), and during timber supply projections using forest estate models such as Woodstock or FORMAN, each stand is tracked along the appropriate set of curves. In New Brunswick, provincial legislation requires that AAC be determined as the nondeclining long-run sustained yield from 80-year timber supply projections. Management planning must also include wildlife habitat and biodiversity considerations as well as timber.

There has tended to be a substantial increase in the number of classes used to characterize the forest in New Brunswick in recent years. Three Crown Licenses, covering areas ranging from 134,000 to 403,000 ha, each identified 30 to 66 "basic strata" based on species groupings, crown closure, and ecological unit. However, the number of yield curves used was much higher, at 103, 394, or 561. Yield curve classes were defined based on 10 to 19 species groups, 5 development stages, 3 to 5 site classes, 2 to 3 density classes, and 5 to 8 silvicultural treatments.

The initial version of PROPS calculated *absolute* volume loss, in cubic meters per hectare, for every yield curve class used by industry planners. In the first test implementation on the Repap N.B. Inc. Crown License 4, based on 1992-1997 management plan information, there were 85 forest classes. However, subsequent operational implementation of PROPS for that and other landbases, using 1997-2002 management plan information, typically involves 400 to 500 classes, as a result of adding other factors into stratification. This substantially increased the effort involved in PROPS implementation, and resulted in changing PROPS to determine *relative* (percentage) volume reduction as a function of classes based on factors that cause differential budworm impact, rather than for all forest classes deemed significant in projections by forest planners. In PROPS, 13 species composition classes in natural stands were based on spruce-fir, hardwood, and other softwood content; seven treated stand classes were based on thinning, planting, and spruce-fir content; and one nonsusceptible stand type (spruce-fir <10 percent) was included. Volume losses for each of the 20 susceptible stand types were calculated for immature (0 to 40 years), mature (41 to 80 years for fir; 41 to 100 years for spruce), and overmature (>80 years for fir; >100 years for spruce) age classes in natural stands, and for two age classes of silviculturally treated stands (0-20, >20 years). This resulted in a total of 54 budworm impact classes, substantially less than the number of forest management planning strata. In PROPS, each forest management planning stratum is matched with the appropriate budworm impact class, and relative volume loss for that budworm impact class is used to calculate absolute volume loss for the stratum. Relative volume losses for mature stands ranged from 33 to 51 percent for normal budworm outbreak and from 51 to 71 percent for severe budworm outbreak scenarios.

CONCLUSIONS

Accurate forest inventory and monitoring data are critical prerequisites for sustainable management planning. In the spruce-fir forests of eastern North America, outbreaks of spruce budworm cause more uncertainty about future forest productivity and structure than just about any other factor. This has prompted the development of the Spruce Budworm DSS, which uses forest inventory and budworm monitoring data, along with a stand growth model, timber supply (or forest estate) model, interpretation rulebases, GIS, and computer technology, to calculate volume losses and effects of management strategies.

In essence, DSS can be viewed as a "value-added" conversion of inventory and monitoring data. Availability of accurate, up-to-date, digital (GIS-based) forest inventory data is a prerequisite to decision support. The raw monitoring data on spruce budworm population level (number of second instar larvae on sample branches) and aerial sketch-map defoliation form inputs into a modeling system to determine stand- and forest-level effects on current and future volume and forest structure. Stand structure changes or productivity estimates are more meaningful values for decisionmaking than are number of budworm or percentage defoliation.

Given the necessity of digital data in a GIS and full coverage of the landbase of interest for use in DSS, remote sensing methods of data collection for monitoring and inventory will undoubtedly become more important in the future. Remote sensing is currently workable for some of the easy-to-detect forest changes, such as areas harvested or burned, but requires further development for most stand development changes.

The real value of decision support systems lies in the ability to do "what if" scenario planning analyses to determine effects of alternative disturbance or management regimes, including doing nothing, on future forest growing stock, sustainable harvest levels, wildlife habitat, etc. These analyses can then be used to determine relative costs and benefits, in terms of timber volume, dollars, or other values. The uncertainty caused by our inability to accurately predict the timing of a natural disturbance event, such as fire or a pest outbreak, can be overcome by evaluating scenarios that bound the likely timing and effects—thinking in terms of "best case," "worst case," and "most probable" scenarios is often helpful.

The province of New Brunswick was one of the first jurisdictions in North America to establish a GIS-based forest inventory. Beginning in 1982, new 1:12,500 color aerial photography was interpreted for the whole province, and NBDNRE actually had the first-ever ARC/INFO license. New Brunswick is now annually updating for harvest, silviculture, and burned areas, and is reinventorying the full landbase on a 10-year cycle, concentrating on updating attributes of existing stand polygons for "slow" stand development changes. The availability of over 15 years of GIS-based inventory data has facilitated the development of timber supply and wildlife habitat modeling, DSS for pest management and harvest scheduling, and advanced ecological land classification systems. Some of the monitoring and inventory lessons learned in attempting adaptive management using GIS databases, now into its fourth 5-year planning cycle in New Brunswick, include: (1) the importance of continuing efforts to calibrate and validate stand projection models, to decrease uncertainty; (2) the value of an extensive permanent plot network to provide empirical data for growth and yield calibration/validation; (3) the efficiency of cooperative industry/government efforts to maintain PSP networks and develop growth and yield estimates, rather than "each forest company on its own"; (4) the importance of monitoring and accounting for natural disturbance factors in sustainability and forest structure projections, if natural disturbance is causing major effects; and (5) the efficiency of basing forest stratification for natural disturbance estimation on impact relationships between pest damage and stand characteristics, rather than using the timber supply or management planning stratification.

ACKNOWLEDGMENTS

Development and testing of the Spruce Budworm DSS has been conducted by the Canadian Forest Service-Atlantic Forestry Center Pest DSS Group, including Kevin Porter, Wayne MacKinnon, Kathy Beaton, Gerry Cormier, and Shawn Morehouse. Initial versions of the Spruce Budworm DSS Protection Planning System and Inventory Projection System were developed by Thom Erdle and Vanguard Forest Management Services Ltd., and by Ian DeMerchant, respectively. Funding has been provided by the Canada Green Plan, Canadian Forest Service, Forest Protection Ltd., N.B. Department of Natural Resources and Energy, Fundy Model Forest, eight forest companies in New Brunswick, SOPFIM, Daishowa-Marubeni International Ltd., and Alberta Environmental Protection. This paper was reviewed by Kevin Porter and Wayne MacKinnon, Canadian Forest Service, Fredericton, NB, Canada.

LITERATURE CITED

Blais, J.R. 1983. Trends in the frequency, extent, and severity of spruce budworm outbreaks in eastern Canada. Canadian Journal of Forest Research. 13: 539-547.

Carter, N.E.; Lavigne, D.R. 1993. Protection spraying against spruce budworm in New Brunswick 1992. Fredericton, NB, Canada: New Brunswick Department Natural Resources and Energy. 38 p.

Dorais, L.; Kettela, E.G., eds. 1982. A review of entomological survey and assessment techniques used in regional spruce budworm, *Choristoneura fumiferana* (Clem.), surveys and in the assessment of operational spray programs. Report Commission for Standardization of Survey and Assessment Techniques. Quebec, Canada: Eastern Spruce Budworm Council, Quebec Department Energy and Resources.

MacLean, D.A. 1980. Vulnerability of fir-spruce stands during uncontrolled spruce budworm outbreaks: a review and discussion. The Forestry Chronicle. 56: 213-221.

MacLean, D.A. 1990. Impact of forest pests and fire on stand growth and timber yield: implications for forest management planning. Canadian Journal of Forest Research. 20: 391-404.

MacLean, D.A. 1996. The role of a stand dynamics model in the spruce budworm decision support system. Canadian Journal of Forest Research. 26: 1731-1741.

MacLean, D.A. 1998. Landscape management for restructuring forest areas. In: Nabuurs, G.J.; Nuutinen, T.; Bartelink, H.; Korhonen, M., eds. Forest scenario modeling for ecosystem management at landscape level; 1997 June 24 -July 4; Wageningen, The Netherlands. Proc. No. 19. Joensuu, Finland: European Forest Institute: 25-45.

MacLean, D.A.; Erdle, T.A. 1986. Development of relationships between spruce budworm defoliation and forest stand increment in New Brunswick. In: Solomon, D.S.; Brann, T.B., eds. Environmental influences on tree and stand increment; 1985 September 23-27; Durham, NH. Misc. Publ. 691. Orono, ME: Maine Agriculture Experiment Station, University of Maine: 106-115.

MacLean, D.A.; MacKinnon, W.E. 1996. The accuracy of aerial sketch mapping of spruce budworm defoliation in New Brunswick. Canadian Journal of Forest Research. 26: 2099-2108.

MacLean, D.A.; MacKinnon, W.E. 1997. Effects of soil drainage on susceptibility and vulnerability of balsam fir to spruce budworm in New Brunswick. Canadian Journal of Forest Research. 27: 1859-1871.

MacLean, D.A.; Porter, K.B. 1994. Development of a decision support system for spruce budworm and forest management planning in Canada. In: Decision making with GIS - the fourth dimension: proceedings, GIS '94, 8th annual symposium on Geographic information systems; 1994 February 12-14. Vancouver, BC: Polaris Conferences Inc. 2: 863-872.

MacLean, D.A.; Porter, K.B. 1995. A DSS for budworm and forest management: maximizing protection benefits and forecasting inventories. In: Power, J.M.; Strome, M.; Daniel, T.C., eds. Proceedings, Decision support 2001; 1994 Sept. 12-16; Toronto, ON. Bethesda, MD: American Society of Photogrammetry and Remote Sensing: 530-540.

MacLean, D.A.; Porter, K.B. 1996. The role of forest inventory projection in the spruce budworm decision support system. In: Shore, T.L.; MacLean, D.A., eds. Proceedings of the workshop on Decision support systems for forest pest management; 1995 October 14-19. FRDA Rep. 260. Victoria, BC: Canadian Forest Service, Pacific Forestry Centre: 15-24.

MacLean, D.A.; Porter, K.B.; MacKinnon, W.E. 1997. Using the spruce budworm DSS to help define protection policy. In: Integrating spatial information technologies for tomorrow, proceedings GIS'97, 11th annual symposium on Geographic information systems; 1997 February 17-20; Vancouver, BC. Fort Collins, CO: GIS World Inc.: 94-98.

Power, J.M. 1991. National data on forest pest damage. In: Brand, D.G., ed. Canada's timber resources. Inf. Rep. PI-X-101. Chalk River, ON: Canadian Forest Service, Petawawa National Forestry Institute: 119-129.

Rotherham, T. 1991. Timber harvest statistics: past practice and present needs. In: Brand, D.G., ed. Canada's timber resources. Inf. Rep. PI-X-101. Chalk River, ON: Canadian Forest Service, Petawawa National Forestry Institute: 105-110.

Schoemaker, P.J.H. 1995. Scenario planning: a tool for strategic thinking. Sloan Management Review, Winter 1995: 25-40.

Sterner, T.E.; Davidson, A.G. 1982. Forest insect and disease conditions in Canada, 1981. Ottawa, ON: Canadian Forest Service.

Vanguard Forest Management Services Ltd. 1993. STAMAN stand growth model and Calibration of STAMAN model for defoliation impacts. In: Forest protection planning to sustain long-term wood supplies. Fredericton, NB, Canada: Contract Report to Canadian Forest Service - Maritimes Region: B1-B39, C1-C18.

An Effectiveness Monitoring Program for the Northwest Forest Plan: New Approaches to Common Monitoring Problems

Craig Palmer, Barry Mulder, and Barry Noon

Abstract.—The Northwest Forest Plan is a large-scale ecosystem management plan for federal lands in the Pacific Northwest of the United States. An effectiveness monitoring program has been developed to determine the extent to which the goals and objectives of this Plan are being achieved. Priority resources identified for ecological monitoring include late-successional and old-growth forests, northern spotted owls, marbled murrelets, and aquatic and riparian ecosystems. The challenge in developing the monitoring program has been to integrate all of these critical components into one efficient and responsive program. Our method has been to develop a common prospective monitoring approach, conceptual framework, indicator selection strategy, monitoring design, and data assessment and reporting process. This paper discusses how our proposed approach addresses some common problems encountered by other monitoring programs. We discuss four major areas of utility to others developing ecological monitoring programs: linkage to decisionmaking, basis for indicator selection, ecological foundation for monitoring, and data quality and accessibility.

The Northwest Forest Plan (Forest Plan) represents one of the largest and most comprehensive ecosystem management plans in the world (USDA/USDI 1994). This 100-year plan encompasses 24 million acres of forested lands on 25 management units administered by the U.S. government (18 national forests and 7 Bureau of Land Management Districts) covering northern California, western Oregon, and western Washington. Much of this federal land is intermingled with state and private ownerships. A primary management goal on all lands has been timber management. The Forest Plan was developed in 1993 at the direction of President Clinton to help resolve the conflict over timber management and protection of natural resources such as the northern spotted owl. The plan addresses both ecological and socioeconomic goals to maintain and restore biodiversity, late-successional and old-growth forest ecosystems, sustainable levels of renewable resources, and rural economies. Since forest management is more than a timber management issue, the plan encompasses multiple resource values, and includes management for thousands of terrestrial and aquatic species as well as natural and human-caused processes. The scale and magnitude of this plan represents unique challenges in ecosystem management, adaptive management, and ecological monitoring.

Forest Plan Monitoring

Monitoring all these resources is required by the Forest Plan (USDA/USDI 1994), by applicable laws, and by the courts (Dwyer 1994). Of the three types of monitoring required by the Forest Plan, our efforts to develop a monitoring program addressed only effectiveness (status and trend) monitoring; implementation (compliance) monitoring was developed earlier, and validation (cause and effect) monitoring has not yet been addressed. The primary question effectiveness monitoring addresses is "To what extent are the goals and objectives of the Forest Plan being achieved?" Because of the huge number of resources and issues that could be monitored, initial direction was given to focus on high priority ecological issues, specifically late-successional forests, the northern spotted owl (*Strix occidentalis caurina*), the marbled murrelet (*Brachyramphus marmoratus*), and riparian and aquatic resources; future planning will focus on biodiversity, socioeconomics, and tribal resources. The monitoring results from these efforts will not only address the status of each resource, but will also collectively help address the adaptive management question about the effectiveness of the Forest Plan in meeting its ecological and socioeconomic goals at periodic intervals over the 100-year period.

To develop a monitoring program of this scope, the agencies involved in the Forest Plan established a team of knowledgeable scientists and resource experts. After an extensive review of the scientific literature, including monitoring of literature from a variety of disciplines, they realized there are not many large-scale or successful

---

Research Scientist, University of Nevada-Las Vegas, Las Vegas, NV, USA; Wildlife Biologist, U.S. Fish and Wildlife Service, Portland, OR, USA; and Research Ecologist, Colorado State University, Fort Collins, CO, USA, respectively.

ecological monitoring efforts that can help in developing and implementing a program of this nature. Most documented efforts are conceptual, or they focus on planning and indicator development. Reviews of these programs have documented the problems with both developing and implementing successful monitoring, and the team used the ideas gained from these experiences to develop a framework for an implementable monitoring program to support the Forest Plan (Mulder *et al.* 1999).

LESSONS FROM EXISTING ECOLOGICAL MONITORING PROGRAMS

Although the term monitoring is widely (and maybe too loosely) used, there is little successful experience that contributes to developing a large-scale, long-term monitoring program of the scope and magnitude of the Forest Plan. Monitoring is routinely mentioned in the ecosystem and adaptive management literature as integral to these concepts, but little is said about the difficulty of developing or implementing a monitoring program and little guidance is provided to develop an implementable program that produces the data needed to manage natural resources. In government, monitoring of natural resources has not been routinely nor consistently applied, particularly for large-scale or multiple resource issues (Bella 1997). In most cases, monitoring is handled as unrelated ad hoc activities left to local handling, and funded if or when funds are available. We believe this is due mostly to a lack of understanding of what monitoring is or needs to be, a failure that is not helped by the understatements about monitoring in the literature.

In the development of this monitoring program, existing and planned monitoring programs were reviewed to serve as examples in developing the program for the Forest Plan, but few examples of successful monitoring programs for large-scale ecosystems were found (Noon *et al.* 1999). Most ecological monitoring has focused on single resources often because single issues drive current concerns (which affects funding availability), but also because it is easier to design a program that addresses individual issues. These efforts collect considerable but not necessarily useful data or data that can be integrated across multiple resource values. This review also noted that these types of programs have not contributed to informed management decisions or proved valuable in averting biological crises (NRC 1990, U.S. GAO 1988). In particular, EMAP, one of the largest monitoring programs, has not only shown little evidence of success, but has also been heavily criticized both scientifically and technically (for example, NRC 1995). The review concludes that a fundamental reason for continued failure in the consistent application of monitoring programs may be that the costs are perceived as high in relation to the output, particularly when the output is perceived as an indication of the failure of managers. Thus, there is a reluctance to invest in monitoring by managers, policymakers, and the public.

Monitoring is also more complex than most people or agencies realize, particularly at this scale, and our lack of understanding of ecosystems adds to the complexity. Monitoring is often presented in conceptual or theoretical terms but with insufficient supporting foundation, is vague about what to measure, or lacks focus on key (measurable) variables. Monitoring programs regardless of their scale have mostly (and often extensively) focused on sampling design and methods to measure indicators, but with little thought given to why those indicators need to be measured, what thresholds of change (in the indicator) would result in changes in management, or what types of change (in management) could be made. From the management side, monitoring normally is not institutionalized as a resource program, and so lacks connections to the agency or its decision and budget processes. Agencies exert considerable effort toward data collection, but little if any effort is made on data quality, management, assessment, or reporting to effectively use those data. In summary, it is not surprising that there is little understanding, and in particular, little interest in monitoring. The result, as the review points out, is that most monitoring is given low priority, usually not fully implemented, and almost always insufficiently funded.

APPROACH RECOMMENDED FOR EFFECTIVENESS MONITORING FOR THE NORTHWEST FOREST PLAN

Given the above concerns, the task facing the team was how to construct a monitoring program for the Forest Plan that would address multiple resource issues, would do so in a (relatively) cost-effective manner, and would demonstrate utility toward informing management decisions and policy about future resource management. The lessons learned through our exercise, as discussed in this paper, are applicable to most types of monitoring programs. Rather than providing a summary of the proposed program (Mulder *et al.* 1999), this paper shows how our approach addresses the common problems encountered by other ecological monitoring programs. The four common problems we have selected to discuss are as follows:

1. No link to decisionmaking,
2. Poor basis for indicator selection,
3. Little ecological or scientific foundation, and
4. Lack of emphasis on data quality and accessibility

It is believed that these concepts will be of general utility to others developing ecological monitoring programs.

Linkage to Decisionmaking

The long-term viability of a monitoring program is very much dependent on its support from management. To be supported, a monitoring program must demonstrate its value to management on an ongoing basis. Of particular importance is to make monitoring results an integral component of the decisionmaking process. Developing this linkage to decisionmaking is a challenging task. Our approach considers three separate concepts–all of which contribute to establishing this linkage. These include organizing monitoring within the framework of adaptive management, developing a prospective approach to monitoring that anticipates the results of management decisions, and defining a process of reporting whereby monitoring data are turned into useful information or knowledge for decisionmaking through specific activities.

Adaptive Management

The traditional approach to natural resource management has been to focus considerable effort on initial planning and the implementation of those plans without an ongoing evaluation of the outcomes of those activities. The adaptive management approach has been suggested as a way to improve management over time by allowing for periodic changes in management actions when deemed appropriate (Walters 1986). The role of monitoring in adaptive management is to detect long-term environmental changes, to provide insights to managers about the ecological consequences of these changes, and to help determine if observed changes dictate corrections to management actions (fig. 1).

As shown on the bottom of the figure, a management action leads to a change in environmental condition. The purpose of the monitoring program is to record these changes through measurements and observations. These data must then be summarized and interpreted to assist in improved future decisions. For example, if certain action thresholds for priority resources have been reached, then this information can be reported to management for their evaluation. The adaptive management cycle continues as new decisions are implemented leading to other changes in the environment that are also monitored. Given this model, it is evident that monitoring is conceptually a core component of the adaptive management process. Our approach is constructed to facilitate the adaptive management process for decisionmakers.

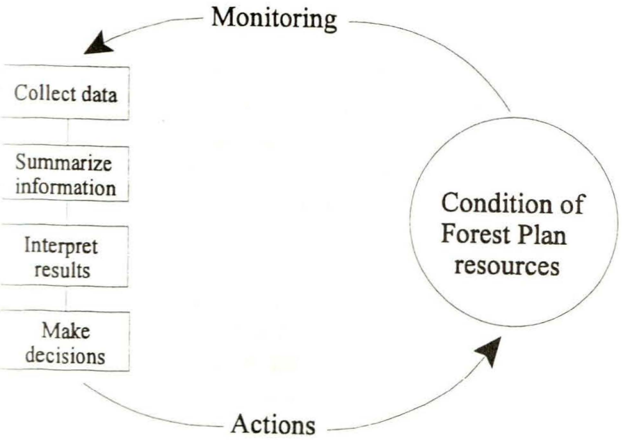


Figure 1.—*Adaptive management cycle where monitoring plays a major role by taking measurements and making observations of key resources to assist in decisionmaking (Adapted from: Keune and Mandry 1996).*

Prospective Monitoring

Monitoring is defined as the "measurement of environmental characteristics over an extended period of time to determine status or trends in some aspect of environmental quality" (Suter 1993). Two different approaches have been suggested to monitoring–retrospective and prospective or predictive (NRC 1995). The retrospective or effects-oriented monitoring approach evaluates changes over time and seeks to explain these changes. Predictive or stress-oriented monitoring also seeks this understanding and then attempts to predict future changes before they become serious. The retrospective approach focuses primarily on measuring ecological effects such as population changes in specific species resulting from stressors that are causing significant ecological effects. The goal of the monitoring program is not only to evaluate current condition, but also to predict future conditions based upon different management scenarios (fig. 2). The prospective approach includes the monitoring of the ecological stressors such as the loss or fragmentation of habitat in addition to the ecological responses to these influencing factors. The prospective approach then anticipates future change based upon a clear understanding of the relationship between stressors and ecological responses.

Given the long delay projected by the Forest Plan between the time that management actions are taken and the response of the ecosystems to those actions, the approach selected for effectiveness monitoring includes retrospective monitoring but has a primary focus on prospective monitoring. During the initial phases of monitoring, measurements of stressors and associated effects of interest will be conducted to assist in the construction of predictive models. Over time, monitoring will emphasize stressor indicators with the use of these predictive models to estimate emerging effects including ecosystem recovery due to the removal of stressors. With an emphasis on anticipated cause-effect relations, an earlier and more focused management response to environmental change is expected. It is also felt that by providing options to

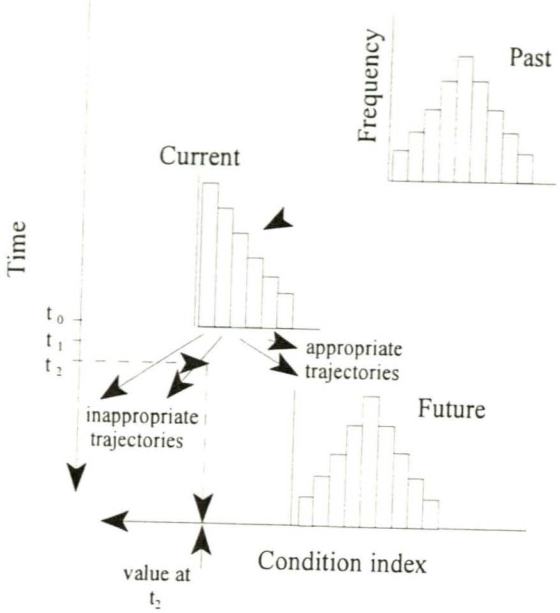


Figure 2.—*Illustration of indicator values showing environmental condition on the landscape at various times where current-to-future changes are a consequence of management intervention (From: Noon* et al. *1999).*

management regarding potential future scenarios, monitoring will become a more integral component of decisionmaking.

Reporting

The purpose of reporting in monitoring is to change measurement data into useful information and knowledge for improved management decisions. Many monitoring programs have collected vast amounts of data without making this important step of interpreting their utility. Our suggested approach is to consider the reporting process as a series of steps (fig. 3). Data are first turned into information when they are collated and summarized. Summary reports would be prepared each year for monitoring data collected for each priority resource module of the effectiveness monitoring program. This is an important first step in the reporting process and provides the added benefit of ensuring that data are organized, validated, analyzed, and reported on a regular basis.

To turn the information provided in summary reports into the knowledge required by decisionmakers, an important second step needs to be taken; the preparation of periodic interpretive reports. These reports consider summary reports, historical as well as all other available data, results of implementation and validation monitoring, research, and ecological models to answer important monitoring questions (fig. 3). This step requires significant effort and planning, but the products of these efforts should be of considerable interest to land managers, policymakers, and scientists. The first interpretive report for the effectiveness monitoring program, planned for the year 2000, will provide the baseline for measuring future change.

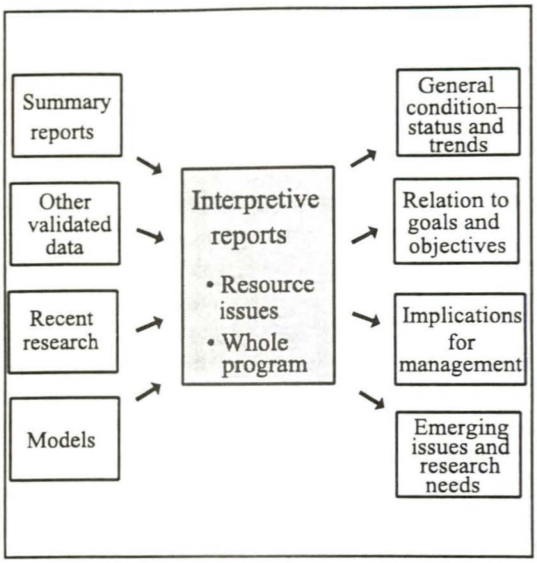

Summary reports
Other validated data
Recent research
Models
Interpretive reports
• Resource issues
• Whole program
General condition—status and trends
Relation to goals and objectives
Implications for management
Emerging issues and research needs

Figure 3.—*Information sources and topics addressed in effectiveness monitoring (From: Palmer and Mulder 1999).*

Indicator Selection

The environmental attributes measured or estimated from a combination of other measurements in a monitoring program are often called "indicators" under the assumption that their values are somehow indicative of the quality, health, or integrity of larger systems (Hunsaker and Carpenter 1990). The selection of indicators for a monitoring program is a very critical step. Even if a monitoring program is fully funded and implemented for many years, it will not achieve its objectives if the wrong indicators are chosen.

Many different approaches have been used for the selection of indicators for monitoring programs. One approach is to select indicators that monitor important values or resources of interest to management. Another approach is to select indicators that make use of the latest technology such as remote sensing and then attempt to interpret monitoring results. Another common method is to convene a workshop and have experts suggest indicators for monitoring and then select priority ones through consensus.

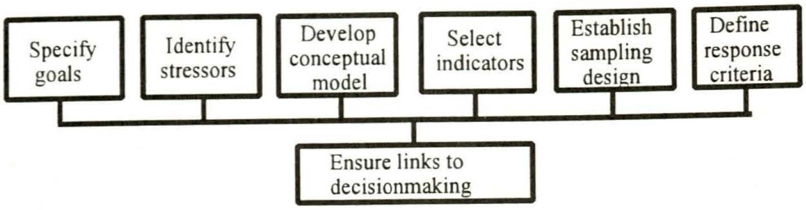


Figure 4.—*Steps in the selection of indicators and development of a monitoring program (From: Noon* et al. *1999).*

Due to our decision to adopt a prospective monitoring approach, a seven-step process (Noon *et al.* 1999) was developed for the selection and implementation of indicator measurements in effectiveness monitoring (fig. 4). The first step is to specify the goals of the monitoring program. The approach we used was to request that each priority resource module develop a list of monitoring questions they would attempt to answer through their monitoring efforts. The process of selecting and reviewing these monitoring questions resulted in a clear definition of the goals for the monitoring program. It was interesting to note that the monitoring questions also suggested attributes or indicators to measure. For example, one monitoring question from the late-successional forests module was: What are the amounts and distribution of forest age classes (including late succession and old growth) at the landscape scale?

The second step is to identify the environmental stressors (natural and anthropogenic) that may compromise the integrity of the ecosystems and their component species and resources. Examples include fire, landscape fragmentation, sediment loading, overharvesting, water diversions, or pollution. To aid in the process of indicator selection, the ecological resources likely to be affected by any given stressor should be identified. It is helpful to consider these for landscape, community-ecosystem, population-species, and genetic components of ecological hierarchies.

The third step is to develop a conceptual model of the relationships between the stressors and ecological responses. This step is often overlooked but is critical to the selection and interpretation of indicator information. Indicators should be selected based on a conceptual model that clearly links stressors and indicators with pathways that lead to effects on ecosystem structure and function (see following section for more discussion on the conceptual model). Once the conceptual model has been completed, candidate indicators can then be selected for monitoring (fourth step).

The fifth step is to establish a sampling design to estimate status and trends for the indicators. One of the most difficult challenges is to determine the value of change in an indicator that indicates a significant biological effect with an acceptable level of uncertainty. With an understanding of the natural spatial and temporal variation in the indicator, a sampling design can be developed to estimate status and trends in the resources of interest.

The sixth step is to determine expected values and trends in the indicator that will trigger a management response. It is recognized that establishing response criteria is difficult due to our incomplete understanding of ecosystems, the lack of pristine ecosystems for benchmark conditions, and nonlinear relations between indicator values and ecosystem processes. The final step, as noted earlier, is to link indicator results to the decisionmaking process through reporting efforts that include data summarization and interpretation with tools such as modeling and statistical decision theory (Conroy and Noon 1996). However, to ensure that this link will take place, it is important to consider the linkages to the decisionmaking process during all previous steps as depicted in figure 4. These last steps are difficult due to our lack of understanding of ecosystems, and require further research.

Ecological Foundation

When developing an ecological monitoring program, it is important to base the scientific approach on a foundation in ecology. Our approach has been to develop a conceptual model for the overall program that can be used as a basis for the establishment of more detailed models for each of the priority resource modules (fig. 5). One conceptual model we have chosen simplifies ecosystem

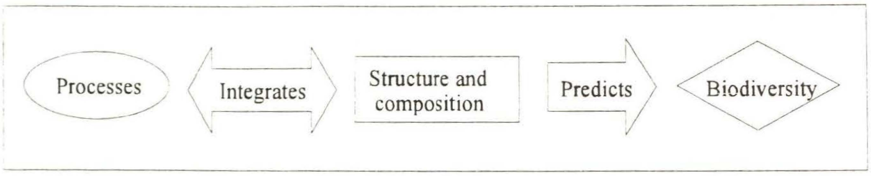


Figure 5.—*Generalized conceptual model illustrating the basis for identifying biological indicators from structural and compositional elements (From: Noon* et al. *1999).*

monitoring by focusing on the structure and composition elements (both landscape as well as stand and microsite characteristics) that express the underlying process and function of the ecosystems (Noon *et al.* 1999). By evaluating these elements in terms of habitat suitability, we hope to provide a substitute for the direct monitoring of numerous biotic populations.

The decision to monitor habitat rather than biotic populations is based on pragmatic as well as theoretical considerations. Our goal is to provide a transition from intensive, individual species monitoring to a more extensive ecosystem approach. The theoretical argument is based on the belief that animals respond to habitat adaptively (Noon 1986). Where an animal selects to live is believed to be an evolved behavioral response stimulated by structural and compositional features of the landscape. The pragmatic argument is that a habitat focus is more in line with land management agencies' missions to manage vegetation communities (habitat), not species populations directly. Monitoring vegetation change is less costly and builds upon existing forest inventory programs. In addition, future changes in forest composition and structure can be predicted through the use of available forest succession models.

The transition to the use of habitat as a surrogate for biotic populations assumes that variables exist that allow for reliable inferences about the integrity of biotic populations of interest. During the initial phases of our monitoring program, we plan to construct predictive models relating habitat to populations. These models will be subject to validation. This validation will be conducted at all spatial scales including the scale of the individual, the local population, and the overall population. A gradual transition will then occur from the monitoring of individual species to the monitoring of habitat with a periodic re-evaluation of the reliability of the predictive models.

Data Quality and Accessibility

The effectiveness monitoring program will build as much as possible upon existing monitoring and inventory programs to help reduce costs. Therefore, it will be important to identify those monitoring programs that can provide essential information for effectiveness monitoring. A diagram identifying the different types of existing programs is presented in figure 6. Our approach will be to first identify those programs providing critical information. Formal ties to these programs will be established including direct data linkages and quality assurance oversight to foster data quality and comparability. Additional effort will also be undertaken to identify those programs providing useful information to effectiveness monitoring for use in interpretive reports.

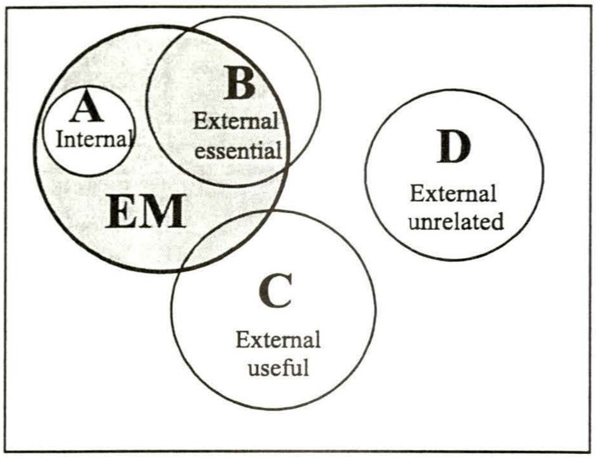


Figure 6.—*Illustration of how data collection activities are related to effectiveness monitoring. EM = data collection needs of effectiveness monitoring; type A = data collection initiated solely for the effectiveness program and internal to it; type B = data collection, initiated for other purposes, that makes a significant contribution to the data requirements of effectiveness monitoring; type C = data collection that provides useful, but not critical data; and type D = data with no apparent connection to the effectiveness monitoring program (From: Palmer and Mulder 1999).*

Finally, regional monitoring programs of the scope of effectiveness monitoring for the Northwest Forest Plan will rely on data collected by a large number of different groups over a long period of time. To be of value, these data must be reliable and comparable. One approach to ensuring data quality is to establish a structured quality assurance program. Quality assurance has been defined as "an integrated system of management activities involving planning, implementation, assessment, reporting, and quality improvement to ensure that a process, item or service is of the type and quality needed and expected by the customer" (ANSI 1994). Although the development of structured quality assurance programs is more common in environmental monitoring programs funded by regulatory agencies, this is a new activity for ecological monitoring programs conducted by land management agencies. However, it was felt that this approach must be followed for effectiveness monitoring to be successful.

CONCLUSIONS

The answer as to whether our approach to addressing the issues presented above will overcome the rather poor legacies of other monitoring programs can come only over time from the test provided by implementation of the program for the Forest Plan. To accomplish this, a number of technical, institutional, and philosophical barriers or challenges need to be overcome; we didn't or couldn't attempt to address them all. For now we believe our focus on a structured and comprehensive approach to development and implementation of a monitoring program for the Forest Plan provides a template for success and is cost effective. The approach emphasizes a scientific foundation for monitoring design, based on the use of conceptual models supported by ecological theory and empiricism to identify appropriate indicators for measurement. This allows a gradual transition from an intensive, single issue focus to an extensive, ecosystem approach that provides periodic reports and interpretations of monitoring results to inform decisionmaking through an infrastructure built around data quality, management, assessment, and reporting.

Future Challenges

Other challenges must also be addressed. Many critical scientific questions surrounding the underlying theory and concepts of ecosystem monitoring can be addressed only through concurrent research that supports the monitoring program, such as developing and refining indicators, developing and testing indicator thresholds for management change, developing predictive models to assess management options, and addressing uncertainty in the monitoring results to help in decisionmaking. The difficulty of addressing these issues is compounded by the large spatial scale of the Forest Plan. As such, research and monitoring are inseparable programs, a fact that unfortunately is not part of our current agency culture.

By far the most critical challenge may be how to institutionalize monitoring into agency cultures as a full resource program with permanent staff, management, and long-term funding—a task that needs to be addressed by management, not research. However, moving to initiate such a fundamental change in agency operations depends on how managers, policymakers, and the public respond to the proposals in this plan. In times of budget shortfalls, the outlook is not positive. Key to this may be in understanding the role and importance of monitoring in adaptive and ecosystem management, and the need for the science community to help provide a basis for understanding, accepting, and desiring a monitoring program and its results. Monitoring and adaptive management should be viewed as synonymous and integral to successful resource management whether it be in support of ecological or socioeconomic goals and where the cost is an accepted part of doing business.

ACKNOWLEDGMENTS

The authors thank everyone who participated in and supported development of the effectiveness monitoring program for the Northwest Forest Plan, particularly the Effectiveness Monitoring Team and the Federal Research Agency executives. We greatly thank the following people who reviewed this manuscript: Dr. Timothy Lewis, Forest Sciences Project, Humboldt State University, Arcata, CA, USA; and Dr. Paul Ringold, Office of Research and Development, Environmental Protection Agency, Corvallis, OR, USA.

LITERATURE CITED

American National Standards Institute [ANSI]. 1994. American National Standard: specifications and guidelines for quality systems for environmental data collection and environmental technology programs. Milwaukee, WI: Energy and Environmental Quality Division, Environmental Issues Group. 55 p.

Bella, D.A. 1997. Organizational systems and the burden of proof. In: Stouder, D.J.; Bisson, P.A.; Naiman, R.J., eds. Pacific salmon and their ecosystems: status and future options. New York: Chapman and Hall: 617-638.

Conroy, M.J.; Noon, B.R. 1996. Mapping of species richness as a tool for the conservation of biological diversity: conceptual and methodological issues. Ecological Applications. 6: 763-773.

Dwyer, W.L. 1994. Seattle Audubon Society, *et al.* v. James Lyons, Assistant Secretary of Agriculture, *et al.* Order on motions for Summary Judgment RE 1994 Forest Plan. Seattle, WA: U.S. District Court, Western District of Washington. 69 p.

Hunsaker, C.T.; Carpenter, D.E., eds. 1990. Environmental monitoring and assessment program: ecological indicators. EPA/600/3-90/060, BP91-14196. Research Triangle Park, NC: Environmental Protection Agency.

Keune, H.; Mandry, P. 1996. Harmonization of environmental data: the requirements for developing a consistent view of the environment world-wide. In: Schroder, W.; Franzle, A.; Keune, H.; Mandy, P., eds. Global monitoring of terrestrial ecosystems. Berlin: Ernst & Sohn: 51-56.

Mulder, B.; Noon, B.; Spies, T.; Raphael, M.; Palmer, C.; Olsen, A.; Reeves, G.; Welsh, H., eds. 1999. The strategy and design of the effectiveness monitoring program for the Northwest Forest Plan. Gen. Tech. Rep. PNW-437. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 138 p.

National Research Council [NRC]. 1990. Managing troubled waters: role of marine environmental monitoring. Washington, DC: National Academy Press.

National Research Council [NRC]. 1995. Review of EPA's environmental monitoring and assessment program: overall evaluation. Washington, DC: National Academy Press. 164 p.

Noon, B.R. 1986. Biometric approaches to modeling—the researcher's viewpoint. In: Verner, J.; Morrison, M.L.; Ralph, C.J., eds. Wildlife 2000: modeling habitat relationships of terrestrial vertebrates. Madison, WI: University of Wisconsin Press: 197-201.

Noon, B.; Spies, T.; Raphael, M. 1999. Conceptual basis for designing an effectiveness monitoring program. In: Mulder, B.; Noon, B.; Spies, T.; Raphael, M.; Palmer, C.; Olsen, A.; Reeves, G.; Welsh, H., eds. The strategy and design of the effectiveness monitoring program for the Northwest Forest Plan. Gen. Tech. Rep. PNW-437. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 21-48.

Palmer, C.; Mulder, B. 1999. Components of the effectiveness monitoring program. In: Mulder, B.; Noon, B.; Spies, T.; Raphael, M.; Palmer, C.; Olsen, A.; Reeves, G.; Welsh, H., eds. The strategy and design of the effectiveness monitoring program for the Northwest Forest Plan. Gen. Tech. Rep. PNW-437. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 69-97.

Suter, G.W. 1993. Ecological risk assessment. Chelsea, MI: Lewis Publishers.

U.S. Department of Agriculture, Forest Service; U.S. Department of the Interior, Bureau of Land Management [USDA and USDI]. 1994. Record of decision for amendments to Forest Service and Bureau of Land Management planning documents within the range of the northern spotted owl. Portland, OR: U.S. Department of Agriculture. 74 p.

U.S. General Accounting Office [U.S. GAO]. 1988. Environmental Protection Agency: protecting human health and the environment. GAO/RCED-880-101. Washington, DC.

Walters, C. 1986. Adaptive management of renewable resources. New York: MacMillan Publishing Co. 374 p.

Evaluation of Habitat Suitability Index Models for Assessing Biotic Resources

John C. Rennie, Joseph D. Clark, and James M. Sweeney

Abstract.—Existing habitat suitability index (HSI) models are evaluated for assessing the biotic resources on Champion International Corporation (CIC) lands with data from a standard and an expanded timber inventory. Forty HSI models for 34 species that occur in the Southern Appalachians have been identified from the literature. All of the variables for 14 models are provided (collected or calculated) from the standard or enhanced inventory and from other sources. Based on these results, we recommend using a land- and habitat-based approach such as landscape ecosystem classification to assess biotic resources because it will more efficiently accommodate all resources.

BACKGROUND

Maintaining biological diversity will be one of the most important environmental challenges of the 21st century. The single-species paradigm for endangered species conservation, largely a byproduct of the 1973 Federal Endangered Species Act, has been, at best, inequitable and, at worst, ineffective. Almost half of endangered species funding is directed toward 10 high-profile species, leaving only half allocated for the remaining 467 species (LaRoe 1993). Funding levels for the 10 high-profile species probably are not inappropriate; nevertheless, many little-known species are being overlooked.

Blunting the increasing loss of biological diversity will require an approach that is linked more clearly with ecological systems (Fiedler *et al.* 1993, LaRoe 1993). One approach to this problem is ecosystem management, a concept that has been conceptualized for decades (Leopold 1966). Such an approach to endangered species management is essential for several reasons. First, resource management problems are more complex than they were even a decade ago. Global issues such as increasing ultraviolet radiation and climate change were hardly considered in the 1970's and 1980's. Also, the legal climate has become more convoluted and confrontational. Second, because issues concerning biological diversity usually transcend jurisdictional lines, a landscape approach to conservation is warranted. However, to be effective, this will have to involve the voluntary cooperation of government (federal, state, and local) and private landowners. Finally, a landscape approach is more cost efficient than the single-species approach. We will never be able to address the inequities inherent in the single-species approach unless we can redirect our focus to the ecosystems that contain them.

It is important to recognize the increasing demands that our growing human population has for natural resources. At the same time, we must recognize that it is more efficient to conserve a species while it is still abundant than when it becomes imperiled. The concept of ecosystem management offers a framework for *a priori* endangered species management, while providing for the production of goods and services upon which humans depend.

This paper presents the results of a study conducted under a contract among Champion International Corporation (CIC), the National Fish and Wildlife Foundation, the National Council of the Paper Industry for Air and Stream Improvement, Inc., the National Biological Service, and the University of Tennessee. The purpose of the research was to evaluate ways of inventorying and monitoring a wide array of biotic resources on private lands in a cost-efficient manner. Specifically, the use of the standard CIC timber inventory with a few additional variables and habitat suitability index (HSI) models was considered.

HABITAT SUITABILITY INDEX MODELS

Habitat suitability index models quantify habitat suitability for species based on environmental variables thought to most affect species presence, distribution, or abundance. HSI models describe habitat suitability for a particular species, not population sizes or trends (Morrison *et al.* 1992). Their output ranges from 0 (totally unsuitable) to 1 (totally suitable) (U.S. Fish and Wildlife Service 1981). HSI models generally are developed species by species, and often are based on both research results and the experience of experts and managers.

Professor, Department of Forestry, Wildlife and Fisheries, The University of Tennessee (UT-FWF), Knoxville, TN 37901-1071, USA; Laboratory Director, Southern Appalachian Field Laboratory, Biological Resources Division, U.S.G.S., Knoxville, TN, USA; and Adjunct Associate Professor, UT-FWF; and Manager, Wildlife Issues, Champion International Corporation, Washington, DC, USA, respectively..

STUDY AREA

The Gulf Tract was chosen as the field site to test the procedures developed as part of this study. It is a 6,700-acre tract owned by CIC in east Tennessee adjacent to the North Carolina border. The terrain is mountainous as is typical of most of the extreme eastern part of Tennessee. The vegetation is predominately mature hardwoods.

FIELD METHODS FOR ENHANCED INVENTORY

An inventory of the Gulf Tract was conducted in July and August 1995. Data were collected on 579 systematically located plots using an enhanced version of the CIC standard timber inventory procedures. Standard timber measurements included tree species, diameter at breast height (dbh), total height, merchantable height for up to three products, age of one tree per plot for site index, and seedling and sapling counts by pine and hardwood. Data collected beyond the standard timber measurements included height to the base of the live crown on merchantable trees; dbh and total height on standing dead trees; percent cover of mid-level vegetation (3 to 15 feet in height); percent ground cover (less than 3 feet in height) from woody vegetation, grass, vines, and other vegetation; length and large-end diameter of down woody material; number of stumps larger than 12 inches in diameter and 12 inches high; and species and dbh for trees with dbh less than 5.0 inches. Merchantable and standing dead trees were tallied on a variable-radius plot. All other data were collected on a 1/50-acre plot.

METHODS FOR DATA COLLECTION

To evaluate the feasibility of using HSI models in inventorying and monitoring biotic resources, we searched the literature for HSI models for species of birds and mammals that occur in the Southern Appalachians. The habitat variables, those variables that are used as input to the HSI models, were recorded and classified into four categories:

1. Standard inventory—variables collected by CIC as part of their standard timber inventory, or that can be derived from data collected as part of the standard timber inventory.

2. Enhanced inventory—variables collected as part of the enhanced timber inventory, or that can be derived from data collected as part of the enhanced timber inventory.

3. Other sources—variables from maps or from a geographic information system that have not been collected specifically as part of the enhanced inventory.

4. Not collected—variables that are not in one of the previous three categories and that must be collected in the field.

RESULTS

Forty HSI models for 34 species of birds and mammals that occur in the Southern Appalachians were evaluated. Table 1 presents the variables and their availability for six HSI models as examples. A table with all of the HSI models is presented in Rennie *et al.* (1997). Examination of these HSI models shows that variables for three species [gray squirrel (*Sciurus carolinensis* Gmelin), hairy woodpecker (*Dendrocopos villosus* (Linnaeus)), and wood thrush (*Hylocichla mustelina* (Gmelin))] were collected, or can be calculated from the standard CIC inventory. Models for six additional species [Acadian flycatcher (*Empidonax virescens* (Vieillot)), black bear (*Ursus americanus* Pallas) (two models), black-throated blue warbler (*Dendroica caerulescens* (Gmelin)), Canada warbler (*Wilsonia canadensis* (Linnaeus)), chestnut-sided warbler (*Dendroica citrina*), and worm-eating warbler (*Helmitheros vermivorus* (Gmelin))] can be used with data that are available from other sources along with the data collected on the standard inventory. Models for two species [downy woodpecker (*Picoides pubescens*) (two models), and hooded warbler (*Hylocichla mustelina*)] can be used with data from the enhanced inventory; one model [eastern wood pewee (*Contopus virens* (Linnaeus))] can be used with data from the enhanced inventory and from other sources. The remaining 26 models require additional data that must be collected in the field as input variables.

DISCUSSION AND RECOMMENDATIONS

Conducting an inventory and subsequently monitoring biotic resources is an essential part of ecosystem management and sustainable forestry. These inventories, like traditional timber inventories, must be conducted at a reasonable cost whether the land is privately or publicly owned.

Use of HSI models driven by variables collected in timber inventories or enhanced timber inventories appears to be a feasible approach. However, each of the models evaluated was developed separately and contains variables specifically related to the critical needs of the individual species being addressed. When only a few species are of concern, as in a featured species approach to wildlife management, the number of variables needed for the HSI models may be manageable. However, when many species are of concern as with ecosystem management, the number of variables needed to evaluate the models becomes exceedingly large. Also, some of the variables required for HSI models are not derived from plot-based data, or from information available from maps, aerial photographs, or

Table 1.—*Types of input variables and their availability for six habitat suitability index models*

Common name **Genus and species** **Citation**	**Variables in HSI models**	**Source of variable**
Black bear *Ursus americanus* Van Manen and Pelton 1993	Overstory vegetation type	Standard inventory[1]
	Overstory vegetation diversity	Standard inventory
	Elevation	Other sources[2]
	Proximity to streams	Other sources
	Proximity to human activity	Other sources
	Proximity to roads	Other sources
	Proximity to trails	Other sources
	History of vegetation disturbance	Other sources
	Slope	Other sources
	Aspect	Other sources
	Fire history	Other sources
Black-throated blue warbler *Dendroica caerulescens* Bartlett 1995	Stand size	Standard inventory
	Oak hickory forest type	Standard inventory
	Cove hardwood forest type	Standard inventory
	Northern hardwood forest type	Standard inventory
	Elevation	Other sources
Downy woodpecker *Picoides pubescens* Anderson and Shugart 1974	Number of saplings	Standard inventory
	Branch biomass of average tree 1.2-8.4 cm dbh	Standard inventory
	Bole biomass of average tree 1.2-8.4 cm dbh	Standard inventory
	Foliage biomass of average tree 1.2-8.4 cm dbh	Standard inventory
	Stump biomass of average tree 1.2-8.4 cm dbh	Enhanced inventory[3]
Hooded warbler Hylocichla mustelina Bartlett 1995	Cove hardwood forest type	Standard inventory
	Number of trees in the 53-68 cm dbh size class	Standard inventory
	Canopy height	Enhanced inventory
Field sparrow *Spizella pusilla* Sousa 1983	Percent of total shrubs less than 1.5 m	Enhanced inventory
	Average height of herbaceous canopy	Not collected[4]
	Percent canopy cover of grasses	Enhanced inventory
	Percent shrub crown cover	Enhanced inventory
Ruffed grouse *Bonasa umbellus* Doan *et al.* 1997	Forest age class	Standard inventory
	Forest group	Standard inventory
	Habitat diversity within home range size	Other sources
	Proximity to daylighted roads	Not collected
	Proximity to evergreen shrub thickets	Not collected

[1] Variable collected as part of standard inventory or derived from data collected in standard inventory.
[2] Data not collected, but available from other sources.
[3] Variable collected as part of enhanced inventory or derived from data collected in enhanced inventory.
[4] Data not in one of the previous categories; must be collected in the field.

other spatial sources addressable with geographic information systems; they would require a separate inventory to acquire. Two examples are proximity to daylighted roads and proximity to evergreen shrub thickets in the HSI model for ruffed grouse (table 1).

Based on these observations, we conclude that a HSI-based approach coupled with the enhanced CIC inventory is not a cost-effective means of measuring biodiversity. Habitat suitability indices could be calculated for only three species with the standard inventory; indices could be calculated with the enhanced database for only three additional models. Another eight models could be added with additional existing data, but the type of data needed and their sources are so varied that, in practice, model calculations would be time consuming and costly. Furthermore, although all the species associated with the 40 models we examined occur in the Southern Appalachian region, many of these models were developed elsewhere in North America and may not be directly applicable to other geographic regions.

An alternate approach is a land- and habitat-based system. This is in contrast to the animal-based approach of HSI models. Developers of these systems have used different names, but one more commonly used is landscape ecosystem classification. These systems use soils, landform, and vegetation to identify homogeneous site units. Once successional and mature vegetation has been described for each site unit, the importance of each vegetational stage is documented on each site unit for a variety of resources including wildlife. This then serves as the basis for management of the forest resources. One area for which a landscape ecosystem classification has been developed with extensive supporting documentation for various forest and wildlife resources is northwestern Ontario. Classification systems have been developed for the Cumberland Plateau and Highland Rim by Smalley (1986) and are being developed by the USDA Forest Service, Southern Research Station (W.H. McNab, personal communication) for the Blue Ridge Province of the Southern Appalachians. However, these systems do not yet have extensive supporting documentation for forest resources other than timber.

Development of a landscape ecosystem classification system is divided into four phases. In phase 1, a model is developed to predict site units from soil and site factors. Site units are mature forest types within the geographic area under study and are identified through analysis of vegetation, soils, and landform data collected in stands with little indication of disturbance. Phase 2 involves describing the various successional stages that develop in each of the site units. In phase 3, specialists in the resources of concern (e.g., timber, wildlife, recreation) evaluate each of the successional and mature vegetation types from their discipline; for example, a wildlife biologist would rate each vegetation type for the various biological needs of each wildlife species in the area. This results in a matrix of vegetation types by uses with cells indicating the evaluations. Phase 4 involves applying the model to predict the presence of site units on the land area under management and to evaluate the impact of management practices through the matrix developed in phase 3. This step depends heavily on geographic information systems, digital elevation models, and other computer intensive techniques. Finally, model verification and refinement is critical. This should be based on both new research and input from users of the model.

ACKNOWLEDGMENTS

The authors thank Frank T. van Manen, Senior Computer Systems Specialist, Southern Appalachian Field Laboratory, Biological Resources Division, USGS, Knoxville, TN, USA; and Craig A. Harper, Assistant Extension Professor, and William G. Minser, Instructor, Research Associate, Department of Forestry, Wildlife and Fisheries, The University of Tennessee, for their reviews of this manuscript.

LITERATURE CITED

Anderson, S.H.; Shugart, H.H. 1974. Habitat selection of breeding birds in an east Tennessee deciduous forest. Ecology. 55(4): 828-837.

Bartlett, J.G. 1995. Relative abundance of breeding birds and habitat associations of select neotropical migrant songbirds on the Cherokee National Forest, Tennessee. Knoxville, TN: University of Tennessee. M.S. thesis.

Doan, M.A.; Dimmick, R.W.; Buehler, D.A.; Rennie, J.C. 1997. Defining habitat quality for ruffed grouse *Bonasa umbellus* in the southern Appalachians using HSI models. Wildlife Biology. 3: 274.

Fiedler, P.L.; Leidy, R.A.; Laven, R.D.; Gershenz, N.; Saul, L. 1993. The contemporary paradigm in ecology and its implications for endangered species conservation. Endangered Species Update. 10: 7-12.

LaRoe, E.T. 1993. Implementation of an ecosystem approach to endangered species conservation. Endangered Species Update. 10: 3-6.

Leopold, A. 1966. A Sand County almanac (with other essays on conservation from *Round River*). New York, NY: Oxford University Press. 269 p.

Morrison, M.L.; Margot, B.G.; Mannan, R.W. 1992. Wildlife-habitat relationships: concepts and applications. Madison, WI: The University of Wisconsin Press. 364 p.

Rennie, J.C.; Clark, J.D.; Emerson, M.W. 1997. Evaluation of habitat suitability index models for biotic resources. Contract report from the Department of Forestry, Wildlife and Fisheries, The University of Tennessee, Knoxville, to Champion International Corporation. 18 p.

Smalley, G.W. 1986. Site classification and evaluation for the interior uplands. Tech. Publ. R8-TP 9. Atlanta, GA: U.S. Department of Agriculture, Forest Service, Southern Region. 518 p. + introduction.

Sousa, P.J. 1983. Habitat suitability index models: field sparrow. FWS/OBS-82/10.62. [Washington, DC]: U.S. Fish and Wildlife Service. 14 p.

U.S. Fish and Wildlife Service. 1981. Standards for the development of habitat suitability models. 103 ESM. Washington, DC: U.S. Department of Interior, Fish and Wildlife Service, Division of Ecological Service. 162 p.

Van Manen, F.T.; Pelton, M.R. 1993. Data-based modeling of black bear habitat using GIS. In: Proceedings of the International Union of Game Biologists, 21st Congress. Halifax, Nova Scotia: 323-329.

Biological Diversity in the Sikhote-Alin Forests and Measures of its Conservation

V.A. Rosenberg, V.N. Bocharnikov, and S.M. Krasnopeev

Abstract.—Forests occupy 80-90 percent of the Sikhote-Alin mountain forest region. Cenotic and species diversity of its forest vegetation is the highest in Russia. In the Sikhote-Alin forests, about 200 species of trees and shrubs and 6 species of lianas grow; about 1,000-1,100 species of grassy plants and more than 450 species of mosses and lichens are registered. In one phytocenosis of broad-leaved and coniferous forests, up to 15-20 tree species, 10-15 species of shrubs and lianas, 50-70 species of grasses, 12-15 species of mosses and lichens, etc. occur. About 20 tree species make up the forest formations occupying large areas and including forests with *Pinus koraensis*, *Picea ajanensis*, *Larux* spp., *Quercus mongolica*, *Fraxinus manchurica*, *Ulmus propinqua*, *Betula* spp., and other species. In the forest formations of Sikhote-Alin, more than 150 primary and old-growth forest types in 64 groups were revealed. Non-sustainable exploitation, forest fires, and other factors of anthropogenic impact caused the greatest damage to the forests of *Pinus koraensis* and *Fraxinus manshurica*. Their areas have been reduced by half over the last 50 years. An adverse anthropogenic impact on the Sikhote-Alin forests results in losses of biodiversity at all levels. Reducing losses and possibly restoring biodiversity and sustainable development of forest territories requires a prompt complex monitoring of current changes in the forests and appropriate correction of forest resource use; complex multifunctional inventorying of the forest resources as a basis for multipurpose use of forest resources; and specifying of a sustainable harvest providing a long-term continuity of resource use and sustainable development of forest territories.

PHYSICAL AND GEOGRAPHICAL CHARACTERISTICS

The mountain-forest region of the Sikhote-Alin stretches along the coast of the Tatar Strait and the northwestern coast of the Sea of Japan. It consists of a complex system of mountain ridges and plateaus, intermontane depressions, and mountain river valleys. The main watershed of the Sikhote-Alin divides the basins of the right tributaries of the rivers Ussuri and Amur and the rivers falling into the Sea of Japan and the Tatar Strait.

The length of the Sikhote-Alin region is about 1,300 km or almost 10° (42°20'-51°25') by geographical latitude. Its largest width is about 300 km (fig. 1). In the central part of this region, its highest sites are situated—Tardoki-Yani Mountain (2,078 m) and Ko Mountain (2,004 m)—where the obvious traces of the late Quaternary mountain glaciation are observed. In general, the height of the mountains in the Central Sikhote-Alin does not exceed 1100-1200 m. The river net is well developed. Its average density is 0.6-0.8 km/km^2, generally decreasing to 0.4 to the west and increasing to 1.0-1.2 at some sites on the slopes.

The climate of the region is influenced by cold winds from the mainland in winter and by cool, damp oceanic winds in summer. Annual precipitation ranges from 700 to 800 mm at the western foothills to 100-1,100 mm at the eastern macroslope and reaches 1,300 mm (probably more) in the upper mountain belt. Mean winter precipatation makes up 18-20 percent of total annual precipitation. Most rain is observed in the second half of summer in the form of heavy showers, when daily rainfall can exceed 200-250 mm.

Because the territory of the Sikhote-Alin extends far from south to north, the temperature in its different parts varies significantly. Mean annual air temperature in the northern part of the region is +1 to -2°C and in the southern part +4 to +5°C. Absolute minimum temperature ranges from -30 to -52°C; absolute maximum temperature ranges from +35 to +41°C. The warmest months are July and August with mean temperature to +20°C. The coldest month is January with mean temperature from -14 to -20°C. A general tendency is observed: with an increase in height above sea level, the air temperature decreases, on average,

---

Institute Biology and Pedology Far Eastern Branch of the Russian Academy of Science, Vladivostok, and Pacific Institute of Geography Far East Branch of the Russian Academy of Science, Vladivostok, respectively.

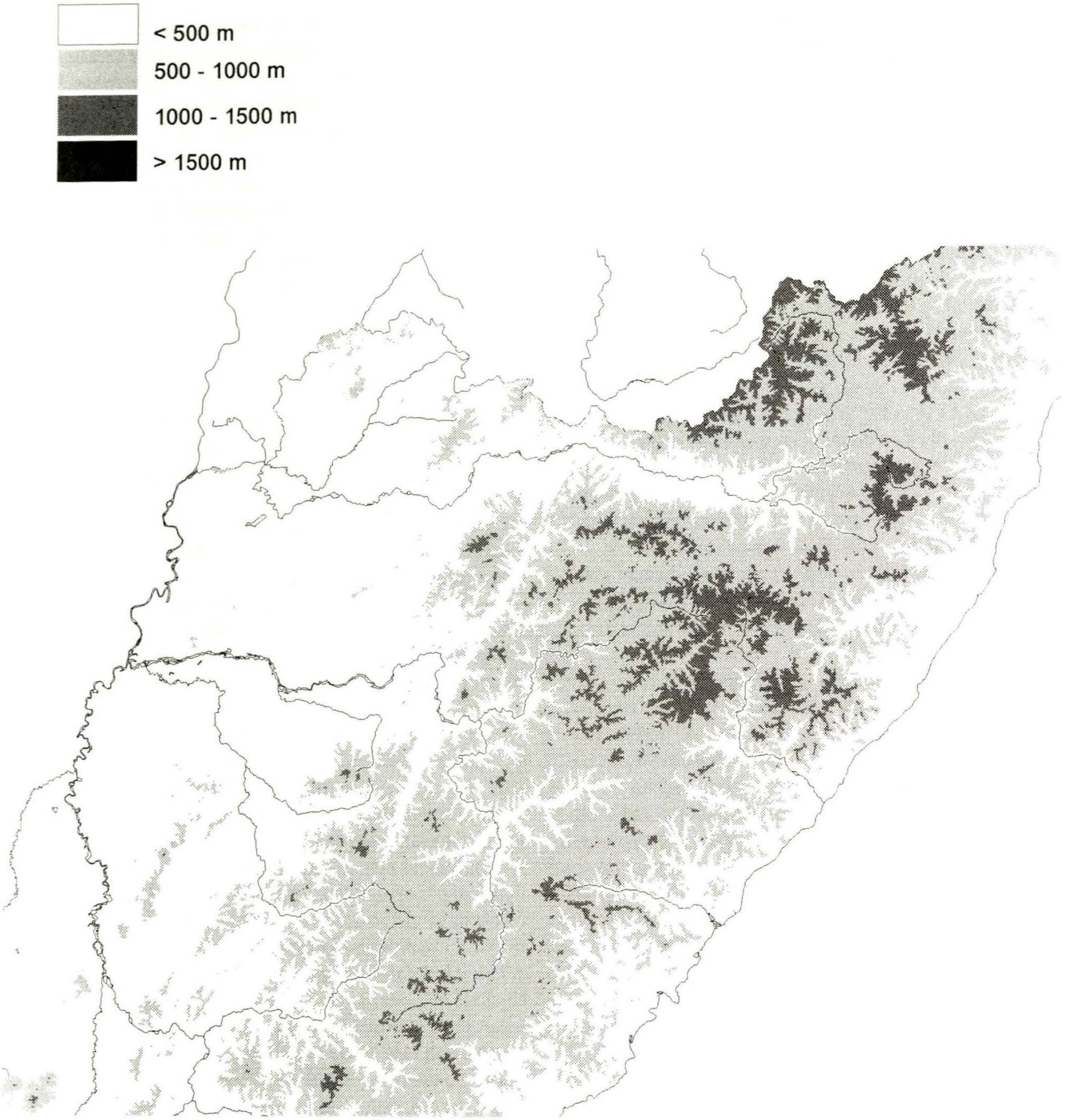


Figure 1.—*Elevations in the Sikhote-Alin region.*

by 0.5°C for each 100 m of the height increase in summer, and it increases by 1.5 to 2°C in winter with an average winter correction factor of 0.1 to 0.3°C.

Forests are common in the Sikhote-Alin region from their upper border to the foot of the mountains. In different parts of the Sikhote-Alin, they occupy 85-95 percent of the total area and, thus, are the main landscape-forming component in this mountain-forest country.

The position of the upper border of straight-boled forests (FUB) in the Sikhote-Alin varies greatly and depends mainly on the geographical latitude of the locality, height, and massiveness of the mountains and their remoteness from the sea. In the southern part of the Sikhote-Alin close to the coast, FUB passes at a height of 1,100-1,300 m. Farther from the sea, it increases to 1,450-1,550 m in the area of the main watershed and to 1,550-1,600 m to the west of it (Oblachnaya Mt.).

In the central Sikhote-Alin, on the largest mountain—Tardoki-Yani Mountain—separated from the sea by high watershed, the forest goes up to 1,450-1,550 m above sea level. Closer to the sea, FUB goes down to 1,000-900 m and less.

The position of FUB in the northern Sikhote-Alin varies more dramatically. At the mountains remote from the sea, it passes at a height of 1,100-1,300 m, and closer to the coast of the Tatar Strait, FUB goes down to 750-800 m above sea level. At the northern end of the Sikhote-Alin close to the latitude 52° north at the capes protruding into the Tatar Strait, FUB is clearly expressed at the hills at an absolute height of only 300 m.

Noteworthy, FUB in the Sikhote-Alin passes significantly lower than in other mountain systems of Eurasia situated at the same latitude. The decrease in the upper border of the distribution of straight-boled forests takes place from the south to the north in two "parallel" rows, one of which passes at the heights of the eastern macroslope of the Sikhote-Alin close to the sea coast, and the other passes along the northwestern macroslope at the heights that do not experience the direct cooling effect of the sea.

Other types of vegetation occupy small areas in the Sikhote-Alin. On the highest mountains, a belt of moss-lichen-bush mountain tundra ("goltsy") is well-expressed. Above FUB, thickets of *Pinus pumila, Rhododendron aureum,* and *Veigela middendorfiana* grow; in the southern part, *Microbiota decussata* and other shrubs and low-lying plants grow. In the Sikhote-Alin there is no belt of typical Alpine meadows, but small sites with mountain lawns are found on wide, flat, and slightly convex saddles and watersheds. In the central parts of the mountain plateaus, sites of oligotrophic swamps with sparse wood and individual trees of *Larix* spp. are observed.

In the forest belt of the Sikhote-Alin, several height bands are distinguished. The upper band is formed of mixed forests of *Betula lanata, Picea aianensis,* and *Abies nephrolepis*. Below, mixed forests with *Picea ajanensis* and *Abies nephrolepis* occupy large areas. The next narrow forest band is formed by *Picea ajanensis* and *Pinus koraiensis*.

With a decrease in height, the contribution of *Pinus koraiensis* increases up to its predominance in the forest stand. Only 35-40 years ago, forests with *Pinus koraiensis* occupied second place in area after forests with *Picea ajanensis* and *Abies nephrolepis.* By now, in the significant part of these forests, *Pinus koraiensis* has been cut out, and *Tillia* spp., *Betula costata,* and other deciduous wood species dominate.

Forests with *Larix* spp. occupy significant areas only in the central and northern Sikhote-Alin. The primary *Larix* forests grow on the overmoist sites of wide river valleys and intermontane depressions and mountain plateaus, and they occupy small areas. The forests with *Larix* spp. that were formed in the place of other forests after fires and felling occupy much greater areas.

In the lower mountain belt of the Sikhote-Alin, the forests occupy significant areas with a predominance of *Quercus mongolica*. A great part of them formed after felling and fires in mixed forests with *Pinus koraiensis* and *Quercus mongolica* and broad-leaved forests with a participation and predominance of *Quercus mongolica*.

The complex of the valley forests is a combination of ecological rows stretching from the low floodplains to the high floodplain river terraces and gently sloping mountain trains. On the low and middle terraces that are constantly flooded by high waters from rain, the forests with *Chosenia* and *Salix* spp. grow. On the rarely flooded terraces, mixed forests of *Chosenia, Populus* spp., *Fraxinus mandshurica, Ulmus*, and others grow. On the intermediate and low above floodplain terraces and slope trains, the forests develop with a predominance of *Fraxinus* and *Ulmus* and complex broad-leaved forests. Other forest formations occupy small areas and are distributed sporadically among the main formations.

STRUCTURE OF BIOLOGICAL DIVERSITY OF FORESTS

In this paper, "structure of biological diversity (BD) of forests" means composition and relationship of levels of formation and manifestation of diversity of wood vegetation.

In this project three levels of BD have been studied in detail. Under the low level, the authors consider an absolute and relative diversity of species composition of forest phytocenoses (in other words, species diversity and species richness). The middle level is diversity of forest types and their primary formations—groups of forest types. As the high level, we include diversity of forest subformations and formations.

Among the mentioned levels of BD, there is, of course, an uncertain number of intermediate as well as lower and higher BD levels, but these three BD levels of forest vegetation are of the most important scientific and practical significance. Besides, the vast materials of state inventories of forest vegetation are available for their evaluation.

The absolute diversity of species composition of forest phytocenosis of the Sikhote-Alin is the greatest in Russia and one of the greatest in the northern temperate belt of Eurasia. In the forests of the Sikhote-Alin, according to different information sources, 1,000-1,300 species of grass vegetation are registered as well as more than 450 species of mosses and lichens. The most diverse species composition is that of broad-leaved coniferous forests. Sometimes up to 20 wood species, 15-20 species of shrubs and wood lianas, 50-70 grass species, and 12-15 moss and lichen species are included in one phytocenosis.

In the forests of the Sikhote-Alin, about 200 species of trees and shrubs grow. Some of the genera are represented by several species: *Acer* (6 species), *Populus* (5), *Betula* (4 or 5), *Tilia* (3), *Picea* (3), *Lonicera* (5), *Ulmus* (3), *Larix* (3), *Rhododendron* (4), *Ribes* (4), *Salix* (more than 10). In the southern Sikhote Alin in the broad-leaved coniferous forests, six species of wood lianas are registered, including *Schizandra chinensis*, *Actinidia arguta*, and *A. kolomicta*. The latter species penetrates into the northern part of the Sikhote Alin and up the mountains to a height of 1,400-1,450 m above sea level The family *Araliacea* is represented by three living forms of plants: grass—*Panax gingseng*, shrub—*Eleuterococcus, Acanthopanax, Echinopanax,* and tree—*Kalopanax*.

The modern BD in the forests at the level of types and groups of types of forests formed as a result of multicentury interaction of ecotopes and bioecological characteristics of the species forming forest phytocenoses. The main determining factor was, and still is, the complex interactions of forest-forming wood species—edificators and ecotopes that determine the course of forest-forming processes: initiation of forest cenosis, its changes with age, destruction and restoration after natural degradation or after felling or fires. The diversity of forest types is closely connected with the diversity of habitat types and forest-growing conditions (ecotopes) corresponding to them. For this reason, the evaluation of diversity of forest types is based on the determination of diversity of habitat types and forest-forming processes in them.

The continuity of natural phenomena determines the necessity of the choice of "scale of division of continuum for the evaluation of BD at cenosis levels. This scale, in our case, is determined by a notion "volume of forest type" discussed below—forest formation.

One forest type includes forest sites occupying similar habitats and having similar productivity. The main forest-forming factor(s) on these sites is one wood species or a stable union of two or more species. The term "forest type" includes all age and short-term restoration stages of development of forest phytocenoses in similar habitats. One group of types combines forest types according to the similarity of their habitat and productivity.

In the forests of the Sikhote-Alin, more than 150 primary and continually stable secondary forest types are distinguished and fixed by forest inventory and planning. Differentiation to the level of forest type is not always necessary for practical purposes, and sometimes it is impossible in industrial conditions. For this reason, the types of forests that develop in relatively similar ecotopes and that have similar productivity were combined into 64 groups of forest types. The highest of the studied levels of diversity of forest vegetation in the Sikhote-Alin includes, according to different sources of information, from 25 to 30 forest formations and subformations.

Fixation of types of forests, forest formations, and subformations by means of forest inventory and planning makes it possible to determine the measures of conservation of BD for certain objects and certain localities, which increases the practical implementation of the measures of exploitation and nature conservation to a significant degree. At the generalized level, 23 primary and stable secondary forest formations and subformations are fixed by means of forest inventory and planning. The rules of felling of general use and improvement thinning are differentiated in accordance with them.

In addition to these forest formations that occupy significant areas, forest inventory and planning take into consideration the forests with a predominance of *Betula lanata, B. mandschurica et B. platiphylla, B. costata, B. dahurica, Salix rorida, S. rotundifolia, Chosenia arbutifolia, Populus amurensis, P. koreana, P. maximowiczii, P. davidiana, Alnus hirsuta*, and thickets of *Pinus pumila* when developing forest management plans.

In the transition bands between territorially and ecologically contiguous forest formations, there are always forests with stable and variable correlation in their composition of the main forest-forming species—edificators of contiguous formations. Such complexes of forest ecosystems are related to the category of subformations. To the same category of subformation can be also related the forests that represent the long-term restoration changes in the primary formations with a participation of long-living pioneer species (for example, forests with *Pinus koraiensis* and *Larix* spp.).

Forest inventory and planning also fixes and characterizes the subformations of mixed forests of *Picea ajanensis et Betula lanata, Pinus koraiensis et Picea ajanensis, Larix* spp. *et Picea ajanensis, Abies holophylla et Pinus koraiensis,* and *Larix* spp. *et Pinus koraiensis*.

In the latter part of the 20th century, the primary main forest-forming species were destroyed by fires and felling on significant territories. When there is no restoration of the primary forest-forming species, their role transfers to the "pioneer" species that settle on the post-felling and post-fire areas. They form secondary but continually stable forests that are classified as independent formations (for example, forests with *Quercus mongolica, Betula costata*, etc.).

The existence of narrowly distributed forest formations is also observed. Some of them, for example the forest formations with *Pinus funebris*, *Alnus japonica*, groves of *Taxus cuspidata* and others, are sporadically distributed on very small areas and are of great botanical and geographical interest. They are all protected by the law, but, unfortunately, the standard methods of state forest inventory and planning do not allow the fixing of rare combinations.

MAIN FACTORS INFLUENCING BIODIVERSITY IN THE SIKHOTE-ALIN FORESTS

Forest biodiversity today is determined in many ways by the cumulative effect of natural and anthropogenic factors. Out of natural factors, a significant effect on forest ecosystems is caused by strong winds that cause windfalls, big floods, and massive damage from pests and diseases. However, the effect of these factors results in relatively short-term local damage in forest ecosystems and a decrease in species BD and, more rarely, cenosis BD. The restoration usually occurs in a natural way during the life span of one or two generations of main forest-forming species—main edificators of forest phytocenoses.

Forest fires cause a greater and longer lasting effect. The only natural cause of forest fires in the Sikhote-Alin is lightning, but this happens quite rarely (about 3 percent of all fires). Even more rare is the recurrence of such naturally caused fires in the same place. Therefore, the negative effect of naturally caused fires is incomparably smaller than those caused by humans. During this decade, the number of fires on the forest territory of the Asian part of Russia has greatly increased, which has caused an increase in the forest area damaged by fires.

But the greatest transforming effect on the forest ecosystems of the Sikhote-Alin is caused by human activities in the forest. The forms of this effect differ, and the most destructive influence is caused by industrial logging operations that embrace significant territories and are called in Russia felling of general use (FGU). The worst consequences are observed in the case of a combination of FGU and fires, especially when they occur many times on the same territory.

In the latter half of the 20th century in the Sikhote-Alin, *Pinus koraiensis* has lost its dominance as a result of **FGU** on almost half of the territories where it once dominated (fig. 2). After the felling of *P. koraiensis,* the predominance status passed to *Tilia mandschurica, Tilia amurensis,* and most of all to *Betula costata*. After industrial felling of *Pinus koraiensis* was prohibited, the volume of FGU significantly increased in the forests with the predominance of *Picea ajanensis*, after which the predominance passes to deciduous species.

As a result of successive combinations of felling and fires in the mixed forests (with *Quercus mongolica*), the area of its predominance has increased sharply, because oak is most resistant to fires. These processes result in a change of dominants in all parts (layers) of forest biocenoses, impoverishment of species and cenosis composition of the forests, convergence of characteristics of species composition and phytocenosis structure, and decrease of their productivity. Such processes to a different degree take place on up to 40-50 percent of the Sikhote-Alin territory.

The greatest transformation of forest ecosystems and the greatest loss of species and cenosis diversity were observed in the southwestern foothills of the Sikhote-Alin. As a result of felling and subsequent numerous fires, coniferous-broad-leaved forests degraded to low bushes consisting of only two layers: tree and shrub layer, where *Quercus, Lespedeza, Corylus*, and some other species grow, and an impoverished grass layer.

At such a degree of degradation, BD losses include 10-15 species of trees, 7-12 species of shrubs, and 40-50 species of grasses. Burning and soil erosion level the conditions of habitats, which in general results in twofold or threefold losses of cenosis BD as compared with the primary one.

MEASURES OF RESTORATION AND CONSERVATION OF BIODIVERSITY IN THE FORESTS OF THE SIKHOTE-ALIN

The influence of unfavorable natural factors on forest ecosystems occurred throughout their evolutionary formation and is one of the conformities of forest-forming processes. Obviously, the measures of restoration and conservation of BD should be adequate to the factors that have a negative transforming influence on forest ecosystems. The possibility of the restoration of BD in the areas where it has been to some degree or other lost depends on the degree of damage of forest ecosystems. The measures of accelerated rehabilitation of windfalls, drying of forests, and other natural damage are known. On the whole, it depends only on the organizational and economical abilities of the human society.

In the parts of the forests of the Sikhote-Alin where, as a result of the felling of coniferous species, deciduous species became dominant, but a sufficient number of coniferous young stand was still preserved, the restoration of the composition and structure of the damaged forest ecosystems occurs, even though very slowly. With the provision of an appropriate protection from fire, it can be expected that more or less full restoration of BD will occur during the life span of one generation of main forest-forming species.

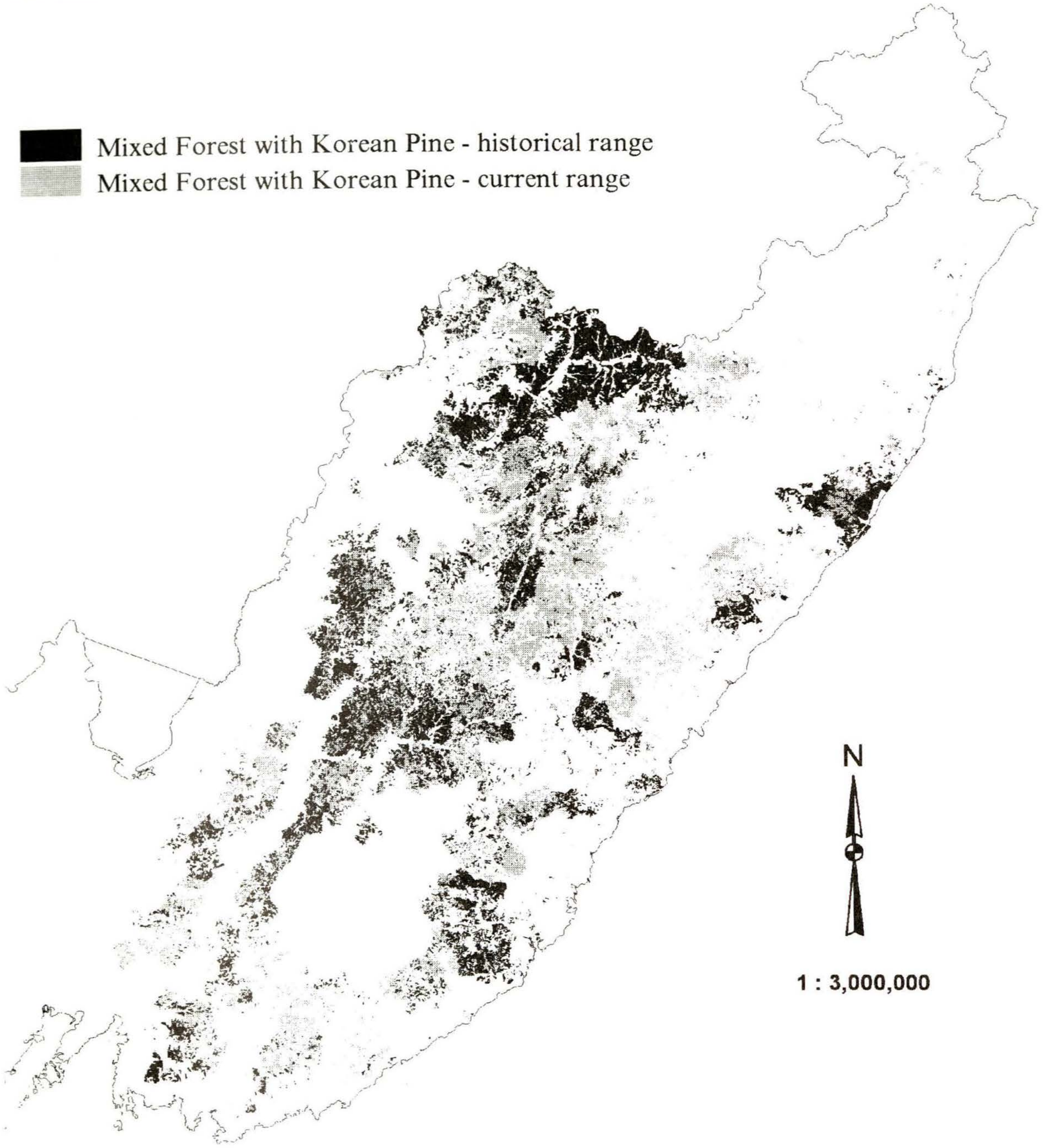

■ Mixed Forest with Korean Pine - historical range
▨ Mixed Forest with Korean Pine - current range
N
1 : 3,000,000

Figure 2.—*Historic and current ranges of the mixed forest with Korean pine (1940-1990).*

In some parts of such areas of young stands, there are no coniferous species or their number is insufficient and a natural source of seed material is lacking. It can hardly be expected that in the near future an artificial planting of coniferous trees will be done there. Therefore, it can be assumed that a number of elements of BD at the species and cenosis levels have been lost for a long time and some of them, probably, forever.

In areas with the greatest degradation of coniferous-broad-leaved forests (to the level of the abovementioned tree and shrub thickets), the full restoration of the former BD in the visible future is practically impossible, because the habitat there has been radically transformed. The necessary and only possible real measure will be the protection of this territory (several hundred thousand hectares in Primorskii krai) from fires, which will help the young stand of *Quercus mongolica* to be restored there.

Considering the already existing negative effects of forest use in the Sikhote-Alin, it is evident measures should be developed promptly for more strict regulation of forest use, which will help conserve BD in the forests that have not been damaged or that have been only slightly damaged by exploitation. This transition to the principles of inexhaustive forest use guarantees a sustainable development of forestry and preservation of the conditions of life sustenance of the aboriginal peoples that live in the Sikhote-Alin and continue to keep their traditional economy.

The forestry status of the forests is of the main importance. In Russia the forests are divided into three groups (categories) in accordance with this characteristic. The first group includes the forests, in which their protective ecological functions are considered to be the main ones (water protection, anti-erosion, health protection, nature conservation, and others, in total over 20 categories of "protection"). The third group includes the forests of the so-called multi-forest areas, in which the industrial (resources) significance of the forests is of the main importance. The forests of the second group occupy an intermediate position. They are considered to be of limited industrial importance. Most commonly they are distinguished in the areas with a scarcity of forests.

Over 70 percent of the forests in the southern part of the Sikhote-Alin and over 80 percent in its northern part belong to the forests of the third group, in which the main method of FGU is clearcutting. However, by the conditions of growing, all forests of the Sikhote-Alin are mountain forests. Use of clearcutting in the mountain conditions contradicts the very essence of their existence, disturbs the local and regional ecological balance, and does not correspond at all to the tasks of the conservation of BD of forest ecosystems at all levels. In such conditions, it is impossible to comply with the main principle of inexhaustive and continuous use of all functions of the forests.

By now in the Sikhote-Alin, there are over 20 confirmed and planned territories of traditional nature management (TTNM) of the indigenous peoples. Clearcutting on TTNM disturbs the conditions of the life sustenance of aboriginal peoples, because it changes to a significant extent the conditions of their living and traditional economy.

We consider these arguments to be sufficient to prohibit clearcutting in the Sikhote-Alin. Practical implementation of such a prohibition is complicated and prolonged, but first and foremost, clearcutting should be prohibited under the following conditions:

- at mountain slopes with a steepness over 15°,
- in all forests of group 1 where they are still permitted,
- in all forests—TTNM of aboriginal peoples,
- in forests of groups 2 and 3 impoverished by previous felling.

It is suggested to also prohibit all kinds of FGU at slopes steeper than 25° and in all the forests at a height of 1,300 m and more above the sea surface, regardless of the form of the landscape and the steepness of the slopes. Therefore, the main kinds of FGU in the Sikhote-Alin should be selective and gradual felling.

It is necessary to permit selective felling under the following conditions:

- at a height up to 750 m above the sea level,
- at plateau-like sites and slopes with a steepness up to 15°—intensity up to 30-35 percent per one felling, with a recurrence in 20 to 30 years,
- at slopes with a steepness over 15°—intensity to 20 percent with the same recurrence,
- at a height over 750 m above the sea level—at all slopes—intensity not more than 20 percent.

Step-by-step felling should be applied mainly in the secondary larch-fir, birch, birch-fir, and birch-larch forests. The duration of step-by-step felling from the first to the last step should be 35-40 years with the main wood species *Picea*, and 20-25 years with the main species *Larix*.

At present, *Pinus koraiensis* and *Abies holophylla* are included in the number of wood species in which FGU is prohibited. But the rules currently in force allow two kinds of felling: "passage" felling that is the final stage of improvement felling before main felling and "sanitation" felling to remove the "sick" trees that supposedly can threaton the "health" of the neighboring trees. The criteria of selecting the trees for these kinds of felling are very uncertain, which allows their subjective interpretation and, as a result, abuse. Previously, before the general prohibition of felling of these wood species for general use, "passage" or "sanitation" felling in the forests was almost never used. Now they are used on a large scale and represent nothing else but disguised prohibited FGU. To preserve BD, it is evident that the notions of "passage" and "sanitation" felling in relation to the species that are especially valuable (*Fraxinus mandshurica*) should be eliminated from use.

A very important thing in the organization of inexhaustive nature management in the broadest sense of this notion is the calculation of permissible annual volume of felling—calculated wood-felling area (CWFA) in case of a clear felling method. As a rule, CWFA that was calculated for large forest management units (forestry unit, state forest enterprise) was used in specific small and medium river basins, for which this felling level was very exhaustive and led to the long-term losses of species and cenosis BD. From now on, until clear felling in the Sikhote-Alin is prohibited, CWFA must be determined for each river basin with an area of not more than 25-30 thousand ha.

As a whole, the discussed measures of the regulation of forest use will make it possible to neutralize gradually the damage that has already been done to BD and to the productivity of the forests of the Sikhote-Alin, and they will prevent the development of some negative tendencies in future forest use. Clearly, in addition to the forest management measures, other measures of BD preservation at all levels are developed and used. They include, for example, the creation of a complex of specially protected territories, the preparation of the materials for the inclusion of a part of the Central Sikhote-Alin in the "Nature World Heritage List," and other actions, but their suggestion and discussion are beyond the framework of this communication.

ACKNOWLEDGMENTS

Part of this project was financed through the ERT-project, which received a grant from USAID and was carried out in 1995-1997 in Khabarovskii Krai and Primorskii Krai. Organizational support was given by N. Moraleva from the Russian office of WWF.

Tracking the Health of Trees Over Time on Forest Health Monitoring Plots

Jim Steinman

Abstract.—The Forest Health Monitoring (FHM) Program was initiated in 1990 as a cooperative effort between the USDA Forest Service and the National Association of State Foresters. Program efforts include detecting changes in tree health from a national grid of one-sixth acre permanent sample plots. Tree data have been collected in various states since 1991, and include species, diameter at breast height (dbh), status (live, dead, or cut), and various ratings of crown condition and damage.

In this study, remeasured tree data were used to track changes in health over a 4-year period, by using status (live, dead, or cut), crown dieback, transparency, and density, and damage measurements of type, severity, and location. Initial analyses identified categories of individual crown and damage measurements associated with trees that eventually died. These thresholds were then integrated into categorical models to estimate the probability of mortality for trees with different combinations of crown and damage conditions. Separate models were constructed for different groups of tree species, with the premise that each group has a unique set of tolerable amounts of damage and foliage loss. Analyses also included statistical tests to verify differences among models.

Results will be incorporated into a field guide for use by land managers to help assess tree health, predict the likelihood of mortality, and rate the health of forest stands. Use of this tool will also help foresters make silvicultural decisions to select trees to be cut when regeneration, thinning, pre-salvage, or salvage operations are considered.

The Forest Health Monitoring (FHM) Program was initiated in 1990 as a cooperative effort between the USDA Forest Service and National Association of State Foresters. A main objective of the program is to detect spatial and temporal changes in tree health from a national grid of permanent sample plots. The health of individual trees is assessed by collecting quantitative measurements of different crown conditions and types of stem and root damage. Several years of data have now been collected from 18 states and summarized (Stolte 1997).

To date, the FHM program has focused on reporting descriptive statistics of measured values of tree health. However, interpretations of differences among tree species, locations, and measurement years are limited without a corresponding knowledge of what values represent healthy and unhealthy trees. Conversely, evaluations of tree health could be improved if models depicting overall conditions of trees were based on an integrated set of health indicators (Gillespie 1995).

The primary purpose of this paper is to provide additional meaning to values of tree health indicators by relating them to tree longevity. Analytical methods were used to first identify the best integrated set of indicators of imminent tree mortality. These indicators were then used to quantify critical conditions that precede tree death. Additional analyses determined how far in advance dying trees can be distinguished from ones that survive. Associated procedures were used to evaluate the conditions of trees that are cut for comparison with conditions of trees that die or stay alive.

METHODS

Available Data

Data used in this study were from 14,791 sampled trees that were annually measured for at least 4 years from 1993 through 1997. Trees were from 648 one-sixth acre plots located in 15 states (Connecticut, Delaware, Maine, Maryland, Massachusetts, Michigan, Minnesota, New Hampshire, New Jersey, Pennsylvania, Rhode Island, Vermont, Virginia, West Virginia, and Wisconsin). The trees from this extensive area were represented by numerous species with no single genus representing more than 20 percent of the sample (table 1). Thus, trees were

---

Research Scientist, USDA Forest Service, Northeastern Research Station, Radnor, PA, USA.

Table 1.—*Frequency of sampled trees that stayed alive, died, or were cut during the measurement period*

Tree genera	Survived (n = 13,513)	Died (n = 598)	Cut (n = 680)	All trees (n = 14,791)
	- - - - - - *Column percentages* - - - - - -			
Maple	21.3	11.4	11.0	20.4
Oak	13.9	7.7	3.2	13.1
Birch	7.4	10.7	3.7	7.4
Aspen/poplar	6.7	8.7	17.1	7.3
Ash	4.1	3.5	1.5	4.0
Yellow-poplar	2.5	0.8	4.9	2.5
Beech	2.3	1.8	0.9	2.2
Hickory	2.2	2.0	0.6	2.1
Basswood	2.0	1.0	0.0	1.9
30 other genera	7.1	11.4	8.4	7.3
All hardwoods	**69.4**	**59.0**	**51.2**	**68.1**
Pine	11.4	13.7	24.0	12.1
Whitecedar	5.7	9.0	0.3	5.6
Fir	5.0	10.0	9.7	5.4
Spruce	4.9	6.0	11.3	5.3
Hemlock	2.5	1.7	2.2	2.5
4 other genera	1.1	0.5	1.3	1.1
All softwoods	**30.6**	**41.0**	**48.8**	**31.9**
All Genera	**100.0**	**100.0**	**100.0**	**100.0**

only analyzed as hardwoods or softwoods to facilitate robust statistical testing. However, the diameter at breast height (dbh) and canopy position of individual trees were used to determine differences in health among overstory and understory trees of different sizes.

Quantitative indicators of tree health used in this study consisted of standardized measures of crown loss and damage to tree stems and surface roots (USDA Forest Service 1997a). Measurements of tree crowns included live crown ratio, and percentages of crown dieback, crown density, foliage transparency, foliage damage or discoloration, and broken branches. Measurements of stem and root damage included severity ratings (in percent) of decay, cankers, resinosis, and wounds. Symptoms of decay were recorded in the field as present or absent and given corresponding severity ratings of 95 or 0 percent in this study. A stem/root damage index value was assigned to each tree by summing the severity ratings of all recorded damages. A better method for calculating a damage index has been developed, but was not available in time for this study (USDA Forest Service 1997b).

Analyses

Preliminary analyses examined the distribution of values for individual indicators of crown loss and stem/root damage (table 2). Live crown ratio and crown density were found to be normally distributed, but all other measures indicative of crown loss and stem/root damage had peaked and right-tailed distributions with means relatively close to zero.

These distributions signify that most sampled trees were in good health, which is not surprising considering only 5 percent of the trees died during the measurement period. Also, the sampled time period and geographic area had no widespread damage from insects, diseases, or weather events. It is more likely that the conditions of the diversity of sampled tree species were influenced by a variety of factors including competition from other trees.

Most indicators were significantly ($p < 0.05$) but weakly correlated with each other (absolute values of r coefficients near 0.2). An exception was crown dieback, which was strongly correlated with foliage transparency ($r = 0.5$), broken branches ($r = 0.4$), and crown density ($r = -0.4$). Crown density was also correlated with foliage

Table 2.—*Means, standard deviations (SD), and skewness (SKEW) of measurements from all sampled trees*

	Hardwoods			Softwoods		
Measurement	**Mean**	**SD**	**SKEW**[1]	**Mean**	**SD**	**SKEW**[1]
Dbh (inches)	9.1	3.8	2.1	8.5	3.3	2.2
Live crown ratio (%)	46.7	18.2	0.5	56.7	22.2	0.1
Crown dieback (%)	5.5	10.6	6.0	4.0	7.8	6.4
Crown density (%)	51.0	13.3	-0.4	49.3	13.5	0.0
Foliage transparency (%)	15.0	9.4	4.4	16.1	7.2	2.5
Broken branches (%)	2.0	10.6	6.9	1.1	7.5	9.7
Foliage damage (%)	0.5	5.2	13.0	0.2	3.6	19.4
Stem/root damage (index)	19.5	43.2	2.4	7.6	27.6	4.4
Decay	16.1	40.1	2.6	5.4	24.2	5.2
Wounding	0.8	6.3	9.9	0.4	5.0	15.5
Cankers	1.2	8.9	10.2	0.2	3.5	17.0
Other	1.3	9.9	8.8	1.5	10.7	8.2

[1] Deviations from zero indicate the degree of skewness where positive and negative deviations indicate right-tailed and left-tailed skewness, respectively.

transparency (r = -0.3) and broken branches (r = -0.3). Tree dbh was not strongly correlated with any of the indicators of tree health.

Discriminant analysis was used as an exploratory tool to identify which measures of crown loss and stem/root damage were most indicative of which trees died one year later. Stepwise methods were used to select the most significant ($p < 0.05$) combination of variables that distinguished trees that died from those that stayed alive. Tested models allowed entry of tree dbh and canopy position as predictors but showed that the best model contained only crown dieback, crown density, and stem/root damage. These were the best predictors for both hardwood and softwood trees, and crown dieback was most significant for each group. Several other measures including dbh and canopy position were statistically significant but relatively weak predictors of tree mortality.

A subsequent procedure was used to determine thresholds of crown dieback, crown density, and stem/root damage that were most frequently associated with tree mortality one year later. A gradient of thresholds was tested using an iterative process that compared percentages of trees that died in differently defined "low" and "high" categories of crown loss or stem/root damage. Chi-square tests of independence were used to select thresholds producing the greatest significant difference in percentages of dead trees between categories.

The final procedure examined changes in crown loss and stem/root damage over the full 4-year measurement period. This was done to determine how far in advance trees that died could be distinguished from trees that survived. Mean values were compared at each year using non-parametric tests because data were not normally distributed. Each measurement was evaluated individually, and hardwoods and softwoods were examined separately.

RESULTS

Critical Thresholds of Crown Loss and Stem/Root Damage

In this study, crown dieback followed by crown density and stem/root damage were found to be the best set of indicators for estimating the probability of trees dying within one year. These were the best measurements for both hardwood and softwood species although each group had a unique set of critical thresholds. Tests to determine critical thresholds of crown dieback showed that hardwoods with more than 30 percent dieback were most likely to die within one year, while softwoods with more than 20 percent dieback were most likely to die within one year. For both hardwoods and softwoods, trees with crown densities less than 30 percent were most likely to die. Critical index values for stem/root damage were 50 for hardwoods and only 20 for softwoods. Foliage transparency and other measures were found to be weaker indicators of tree mortality.

Each category of tree conditions defined by different combinations of crown dieback, crown density, and stem/root damage was found to have a unique percentage of trees that died (table 3). As expected, trees most likely to die were in categories with high dieback, low crown density, and high damage. Conversely, trees with values in opposite categories were least likely to die. Other categories where two measures indicated poor tree health

Table 3.—*Percentages of trees with different combinations of crown dieback, crown density, and stem/root damage that died within 1 year*

a) Hardwoods

Stem/root damage index[1]	Crown dieback			
	≤ 30 %		> 30%	
	Crown density		Crown density	
	> 30%	≤ 30%	> 30%	≤ 30%
	percentage of sampled trees that died (number of sampled trees)			
≤ 50	**1** (7,451)	**9** (463)	**11** (27)	**43** (119)
> 50	**3** (1,352)	**23** (171)	**35** (17)	**62** (68)

b) Softwoods

Stem/root damage index[1]	Crown dieback			
	≤ 20 %		> 20%	
	Crown density		Crown density	
	> 30%	≤ 30%	> 30%	≤ 30%
	percentage of sampled trees that died (number of sampled trees)			
≤ 20	**2** (3,486)	**11** (340)	**21** (24)	**40** (30)
> 20	**5** (335)	**17** (53)	**23** (13)	**59** (29)

[1] The damage index is calculated for an individual tree by summing the percent severities of decay, cankers, resinosis, and wounds.

had greater percentages of trees that died than categories where just one measure indicated a poor health condition. Few trees died without some indication of poor health. This categorical analysis confirmed preliminary discriminant analyses showing that crown dieback was the best but not the solitary indicator for distinguishing which trees died.

Early Symptoms of Impending Mortality

Other analyses compared the amount of crown loss and stem/root damage that trees had 2 and 3 years prior to death or their most recent measurement if they survived. Crowns of trees that died had noticeably more dieback and lower densities than trees that survived for as long as 3 years before death (figs. 1 and 2). Damage was also greater in trees that died but at constant amounts throughout the measurement period (fig. 3). Mean values of crown dieback, crown density, and stem/root damage for trees that survived and trees that died were significantly different 1, 2, and 3 years before their most recent measurement. Differences between live and dead trees were more pronounced in hardwoods than in softwoods.

Values of foliage transparency were also compared even though this was not as good as an indicator to predict mortality (fig. 4). Hardwood trees that died had an average foliage transparency that was greater than the transparency of trees that stayed alive for at least 3 years before death. However, the difference in transparency between trees that died and those that stayed alive was less distinguishable for softwoods.

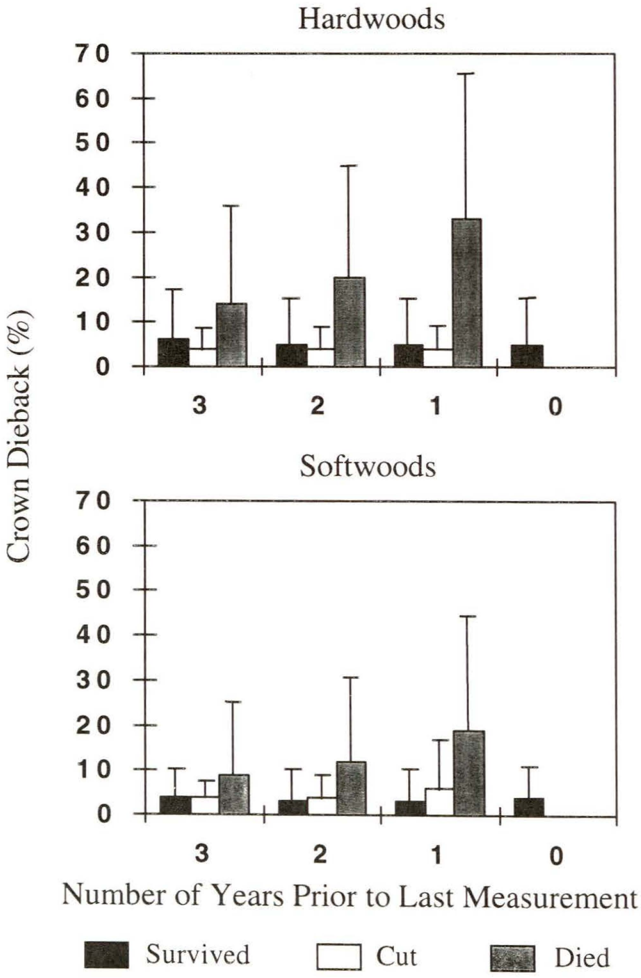


Figure 1.—*Average annual changes in crown dieback of trees that survived, died, or were cut.*

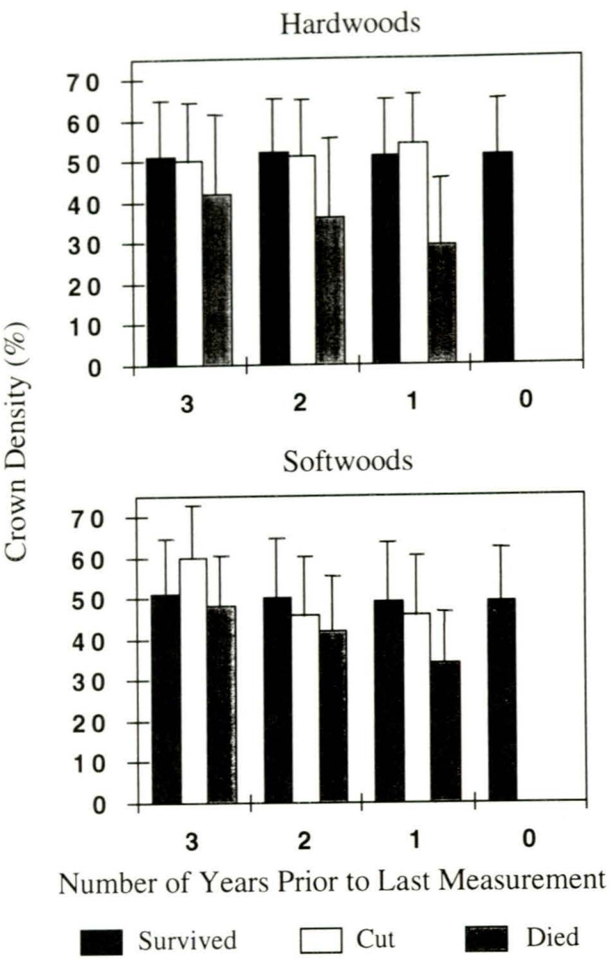


Figure 2.—*Average annual changes in crown density of trees that survived, died, or were cut.*

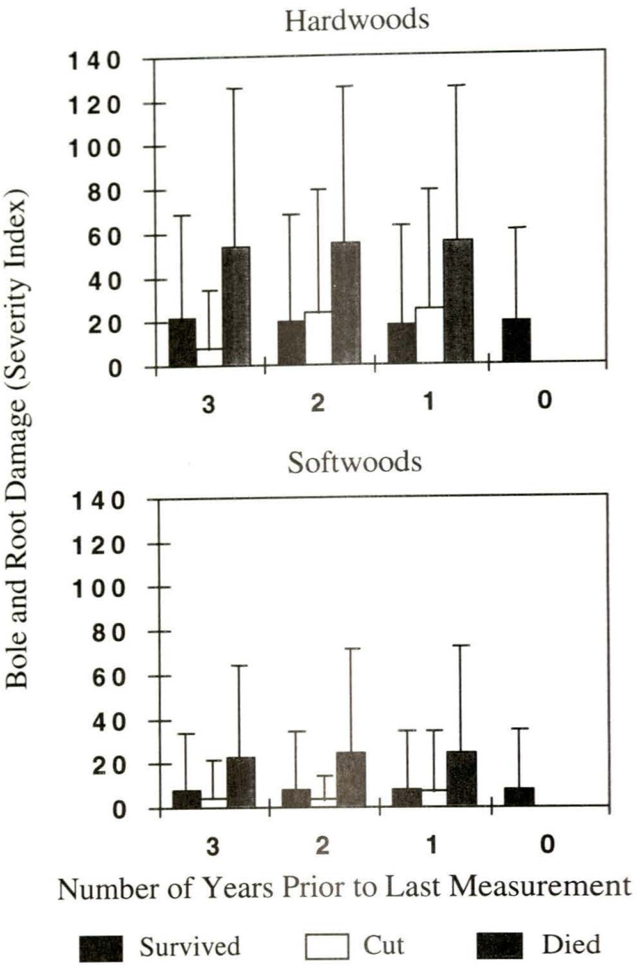


Figure 3.—*Average annual changes in stem and root damage of trees that survived, died, or were cut.*

Secondary results showed that conditions of trees that were eventually cut were more similar to trees that stayed alive than to trees that died (figs. 1 through 4). At each year before the most recent measurement, values for crown dieback, crown density, stem/root damage, and foliage transparency of trees that were cut were almost equal to those for trees that stayed alive.

DISCUSSION

Precision of Estimates

Some uncertainty remains about the precision of estimates in this study even though results show relationships that could be useful. As mentioned, trees were sampled from an extensive and diverse geographic area, which prevented stratifying the data to examine specific relationships for individual tree species or sites. Measured conditions indicate that the vast majority of trees were in good health as indicated by the relatively low percentage of trees that died or had poor crowns and severe damage. The selected set of indicators and their critical thresholds should both be validated before use.

Even so, results from analyses of the health conditions of sugar maple (*Acer saccharum*) conducted by the North American Maple Project (NAMP) were comparable to those found in this study (Allen *et al.* 1995). Crown dieback exceeding 35 percent was found to be a key indicator of imminent mortality, and less than 5 percent of all live sugar maple were observed to have greater amounts. Results were also comparable to this study in that foliage transparency was found to be a poor predictor of mortality and poorly correlated with crown dieback. Crown density and damage to stems and roots of sugar maple were not available for comparison with measurements from this study.

Continual measuring of existing FHM plots will provide additional data to track trees for a longer period of time. Data from the 1998 field season will be available in about 6 months and could help validate findings in this study by showing the fate of live trees that had poor crowns in

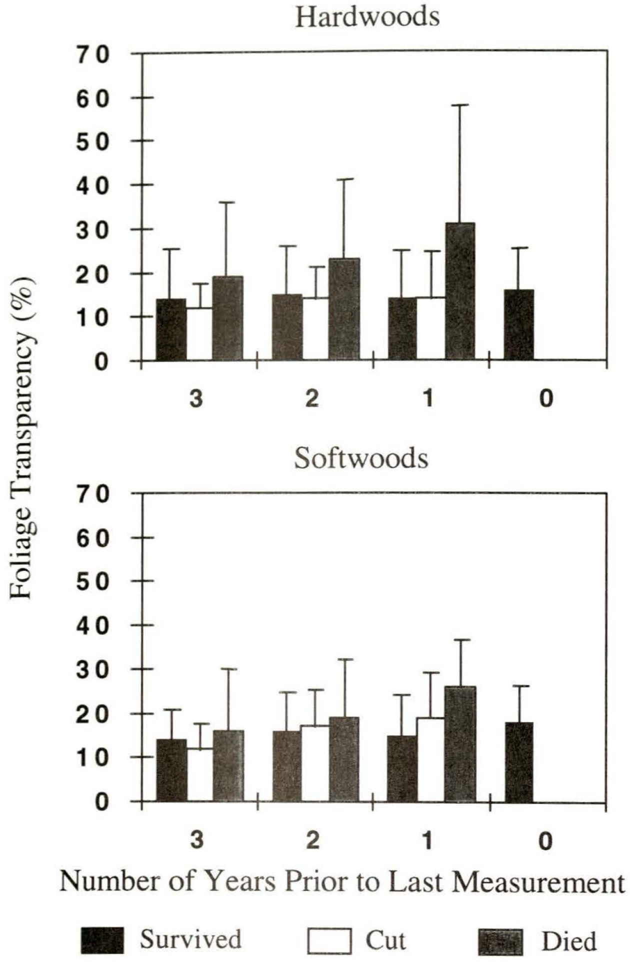


Figure 4.—*Average annual changes in foliage transparency of trees that survived, died, or were cut.*

1997. Other future interests will include using a more refined damage index that is currently being developed (USDA Forest Service 1997b). This index will adjust the severity ratings of stem damage as related to where they are located, with damages close to the ground receiving the highest ratings.

Potential Applications

Information about critical conditions of crown loss and stem/root damage indicative of tree mortality has two potential uses. One use would be to incorporate this information into the reporting component of the Forest Health Monitoring Program. Reports showing which sample plots contain trees with threshold conditions could help identify locations with tree health problems. Depictions of percentage of trees on individual plots that have threshold conditions could also be more informative than alternative representations that show average values of indicator measurements.

Information from this study may also be useful as a forest management tool to help decide which trees to remove during silvicultural treatments. Results imply that trees with good crowns and little damage were purposely selected to be cut over weaker trees. Current harvesting trends in the northeastern U.S. correspond to this premise considering that many stands are selectively cut (high-graded) for the most merchantable trees (Smith 1986).

Most foresters are skilled at rating the health of trees based on the overall appearance of crowns and stems. However, there is still a need to accurately select high-risk trees during harvesting operations and convey this technique to non-industrial private landowners who cut their own trees. A transfer of this information could be a valuable means to improve forest stewardship efforts.

ACKNOWLEDGMENTS

I thank the following people from the USDA Forest Service, Northeastern Research Station, Radnor, PA, for reviewing this manuscript: Stan Arner and Rich Widmann, Forest Inventory and Analysis Program; and Charles Barnett and Barbara O'Connell, Forest Health Monitoring Program.

LITERATURE CITED

Allen, D.C.; Molloy, A.W.; Cooke, R.R.; Lachance, D.; Barnett, C. 1995. North American Maple Project: seven year report. U.S. Department of Agriculture, Forest Service. 57 p.

Gillespie, A.J.R. 1995. Research and development needs for forest ecosystem monitoring. In: North American workshop on monitoring for assessment of terrestrial and aquatic ecosystems; 1995 September 18-22; Mexico City, Mexico. Gen. Tech. Rep. RM-284. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Smith, D.M. 1986. The practice of silviculture. New York, NY: John Wiley and Sons, Inc. 527 p.

Stolte, K.W. 1997. 1996 national technical report on forest health. Admin. Rep. FS-605. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station. 47 p.

USDA Forest Service. 1997a. Forest health monitoring 1997 field methods guide. Research Triangle Park, NC: U.S. Department of Agriculture, Forest Service, National Forest Health Monitoring Program. 325 p.

USDA Forest Service. 1997b. Final report on damage workshop. February 19-20, 1997. St. Paul, MN: U.S. Department of Agriculture, Forest Service, National Forest Health Monitoring Program, North Central Forest Experiment Station.

Development of a Stand-scale Forest Biodiversity Index Based on the State Forest Inventory

Diego Van Den Meersschaut and Kris Vandekerkhove

Abstract.—Ecological aspects are increasingly influencing silvicultural management. Estimating forest biodiversity has become one of the major tools for evaluating management strategies. A stand-scale forest biodiversity index is developed, based on available data from the state forest inventory. The index combines aspects of forest structure, woody and herbal layer composition, and deadwood, as biodiversity indicators. The index is calculated by means of a score system following a standard procedure. It reflects the variability of forests in Flanders in a logical way and is sensitive enough to indicate changes for monitoring purposes.

The Flemish government has committed itself to fulfill the obligations towards biodiversity conservation set out in the UN's Convention on Biological Diversity (Rio de Janeiro 1992), the Resolution on Conservation of Biodiversity in European Forests (H2) of the Ministerial Conference on the Protection of Forests in Europe (Helsinki 1993), the Flemish Environmental Policy Plan, and the new Decree on Nature Conservation and the Natural Environment (1997). Therefore, there is a definite need for monitoring tools for biodiversity in general and forest biodiversity in particular. This study focuses on forest biodiversity, limiting its possible interpretation to its still most important measure of species richness.

Assessing and monitoring species richness is labor intensive, time consuming, and requires specialist knowledge, which makes it inapplicable on a large scale. Total potential species richness is never completely known. Even in intensely investigated European forest ecosystems, new species are still frequently identified. The use of indicators for forest biodiversity is confronted with a range of problems related to a general lack of knowledge (EWGRB 1997). The use of certain well-known taxa as indicators deals with a lack of scientific evidence for the primary condition of an indicator, namely significant correlation with diversity of other taxa. Existing research on this subject even suggests that a single taxon or a combination of taxa cannot serve as reliable indicators for species richness of most other taxa because of contradictory or weak across-taxon correlations (Nilsson *et al.* 1995, Oliver and Beattie 1996). Keystone species, i.e., species that are functionally important for a wider part of biodiversity, could serve as potential indicators of biodiversity, but there seems at present to be insufficient scientific basis or empirical ways to optimally construct an indicator system based on these. Moreover, an a priori problem with species-based indicator systems is that species often have varying ecological demands and/or do not respond similarly to altered conditions in different parts of their distribution.

An alternative approach consists of the use of sets of biological and/or structural indicators. In this study, a biodiversity index is developed on the level of a forest stand based on available data on forest structure and floral species composition from the state forest inventory. It covers easily measurable features of forest structure, woody and herbal layer composition, and deadwood, serving as indicators for biodiversity. The concept of the index and its indicators is based on a virtual image of the authentic structure and composition of primary natural forest ecosystems. Since the Neolithic period, some 10,000 years ago, increasingly intensive human influence has resulted in a loss of the authenticity of most European forests (Christensen and Emborg 1996, Dudley 1996, Peterken 1996). The authentic structure, composition, and dynamics will probably never be entirely detected. Nevertheless, some major aspects of this authenticity can be identified including varied and complex forest structure; rich composition of tree and shrub species; large old trees; deadwood; and characteristic disturbances caused by storm, grazing, pathogens, and fire (Bradshaw and Lindén 1997). The biodiversity index is conceived under the assumption that a varied and complex forest structure induces a high biological richness due to the creation of a diversity of different niches (Altenkirch 1988, Franklin 1988, MacArthur *et al.* 1962, Otte 1989). Because the index will serve as a monitoring tool to evaluate the impact of forest management on biodiversity, a high sensitivity to silvicultural measures is necessary. This requirement rules out other important indicators of biodiversity like site history, connectivity, forest area, and site condition. Moreover, these indicators are rigid in a sense that they are not apt to change at short notice.

Scientific attachés, Institute for Forestry and Game Management, Gaverstraat 4, B-9500 Geraardsbergen, Belgium, Tel.: +32-54-437111, Fax.: +32-54-410896.

STATE FOREST INVENTORY

The state forest inventory of the Flemish region is based on a systematic sampling technique using a geo-referenced grid of 1 x 1 km (Waterinckx and Haelvoet 1997). Due to a low forest index of 10 percent and a high degree of fragmentation (Van Den Meersschaut and Lust 1994), only a limited number of intersections of the grid are actually situated in forest, resulting in approximately 1,500 plots. Each plot is located in the field by means of aerial photographs and shifted into the nearest homogeneous forest stand if necessary, following a standard procedure.

The forest inventory includes a general description of the stand, with special attention to the stand type, age distribution, canopy closure, horizontal and vertical stand structure, combined with measurements of the woody and herbal layer (Waterinckx and Haelvoet 1997). The woody layer is sampled using a plot design of four concentric circular sample units (A1, A2, A3, and A4) with variable radius (R1, R2, R3, and R4) according to the dimension of trees and shrubs (fig. 1). In A1 and A2, only tree species and stem numbers are measured. In A3 and A4, individual trees and shrubs are also positioned using polar coordinates after measuring their circumference at a height of 1.5 m ($C_{1.5}$)[1]. These measurements apply to living as well as dead standing trees (snags). The herbal layer is sampled on the same spot using a 16- x 16-m plot. All vascular plants and bryophytes[2] are identified, and their cover is estimated using an adapted version of the Braun-Blanquet scale (Barkman *et al.* 1964, Braun-Blanquet 1951). Within the plot, special attention is given to the lying deadwood (logs). Logs are divided into four diameter classes (2 < ∅ < 7 cm; 7 < ∅ < 22 cm; 22 < ∅ < 40 cm; and ∅ > 40 cm). Density and stem length of the logs is estimated for the first and last two classes, respectively.

This is the first time that the Flemish forest area has been sampled by means of a systematic technique. The state forest inventory will be repeated every 10 years.

BIODIVERSITY INDEX

The biodiversity index is calculated by means of a score system based on four major aspects of a forest ecosystem determining forest biodiversity: forest structure, woody and herbal layer composition, and deadwood. Each aspect consists of a set of indicators derived from the available data of the state forest inventory. The indicators are given a score taking into account the "Delphi technique," which stipulates that as long as biodiversity cannot be unambiguously measured in the field, biodiversity indicators and their weights or scores can be

---

[1] *$C_{1.5}$ is a traditional local measure easily transformed into diameter at breast height (dbh), which is used for the biodiversity index.*

[2] *The sampled bryophytes include non-epiphytic mosses (Musci) and Liverworts (Hepaticae).*

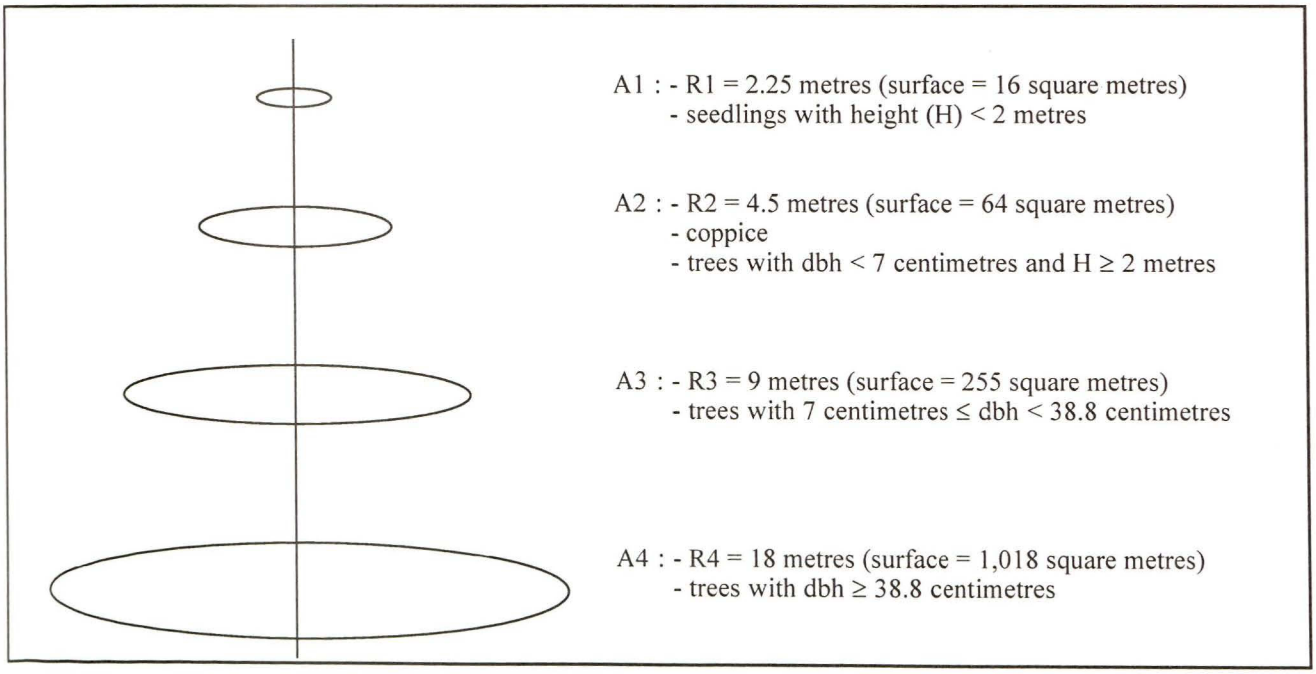

A1 : - R1 = 2.25 metres (surface = 16 square metres)
- seedlings with height (H) < 2 metres
A2 : - R2 = 4.5 metres (surface = 64 square metres)
- coppice
- trees with dbh < 7 centimetres and H ≥ 2 metres
A3 : - R3 = 9 metres (surface = 255 square metres)
- trees with 7 centimetres ≤ dbh < 38.8 centimetres
A4 : - R4 = 18 metres (surface = 1,018 square metres)
- trees with dbh ≥ 38.8 centimetres

Figure 1.—*Plot design for the inventory of the woody vegetation consisting of concentric circular sample units (A1,2,3,4) with variable radius (R1,2,3,4) (after Waterinckx and Haelvoet (1997)).*

determined on the basis of a common agreement of different specialists (table 1) (Alho *et al.* 1996, Dalkey and Helmer 1962, Kangas *et al.* 1993, Pukkala *et al.* 1997). During application of this technique, special attention is given to evenly balancing the weights of the different indicators, presuming their contribution to biodiversity is more or less equal. The maximum score of the biodiversity index is set to 100. Appendix 1 gives a detailed overview of the score system with its indicators and their weights. For the indicators of woody and herbal layer composition and deadwood, the classification of the numbers and maximum values is based on analysis of elaborate data sets from the Flemish forest reserve inventory, in which sample plots of comparable size were used.

Forest Structure

Habitat complexity and structural heterogeneity are generally recognized as important indicators for forest biodiversity (Köhl 1995, Noss 1990, Rune 1997, Schuck *et al.* 1994). The forest structure, mentioned as a biodiversity indicator in this study, is based on a description of the visual characteristics of the whole stand in which a

Table 1.—*Overview of the different indicators and their maximum scores forming the biodiversity index*

Indicator	**Maximum score**
FOREST STRUCTURE (a+b+c+d) :	20
(a) Canopy closure/cover	4
(b) Stand age	7
(c) Number of stories	4
(d) Spatial tree species mixture	5
WOODY LAYER (e+f+g+h+i) :	25
(e) Number of (indigenous) tree species (height ≥ 2 m)	5
(f) Number of large trees (40 ≤ dbh < 80 cm)	5
(g) Number of very large trees (dbh ≥ 80 cm)	5
(h) Number of indigenous tree species in natural regeneration (height < 2 m)	4
(i) Standard deviation of dbh	6
HERBAL LAYER (j+k+l+m) :	25
(j) Number of vascular plant species	10
(k) Degree of rareness	7
(l) Number of bryophytes	5
(m) Total cover	3
DEADWOOD (n+o+p+q+r) :	30
* Snags (n+o+p) :	15
(n) Basal area	4
(o) Number of large trees (dbh ≥ 40 cm)	6
(p) Standard deviation of dbh	5
* Logs (q+r) :	15
(q) Sum of stem-length of large trees (∅ ≥ 40 cm)	7
(r) Number of diameter classes	8
BIODIVERSITY INDEX (a→r)	100

sample plot is located. These characteristics consist of canopy closure or cover, stand age, number of stories, and spatial tree species mixture. Woody layer, herbal layer, and deadwood are also part of what can be called forest structure but are treated separately because they are based on actual measurements.

The closure of the upper canopy layer is considered to be a measure of habitat variation because it causes different light and humidity regimes or microclimatic conditions in general (Noss 1990). A canopy cover of 1/3 to 2/3 of the total area is supposed to offer the biggest structural variety and is thus awarded a maximum score of 4. Open stands (canopy cover < 1/3) score a little higher than closed stands (canopy cover > 2/3) for the same reasons.

A higher stand age positively influences forest structure. Maturing stands diversify naturally providing more opportunities for nesting, shelter and nourishment, which may be important for the survival of different animal and plant species (Helmer 1987, Mitchell and Kirby 1989). Stand age and scores are therefore positively linked. Uneven-aged stands score a little lower than older stands (> 160 years), because an uneven stand age does not automatically imply an old age.

The number of stories is a valuable parameter for describing the vertical structure and diversity of a forest stand. Multilayered forest stands create a higher and more diversified amount of niches, and receive a maximum score.

The spatial tree species mixture is a valuable parameter for describing the horizontal structure of a forest stand. The weighing of the scores is based on the idea of the biggest possible variety on the smallest possible surface resulting in the maximum score for stands with an individual tree species mixture.

Woody Layer

The indicators—number of tree species, number of large and very large trees, number of indigenous tree species in natural regeneration, and standard deviation of $\varnothing_{1.5}$—are based on measurements in circular sample plots.

The tree species composition is a very important indicator of diversity. Many organisms are linked to specific tree species and vice versa (Kennedy and Southwood 1984, Southwood 1961). Mixed forest stands will accommodate more animal and plant species than single species stands. Exotic tree species contribute to biodiversity because a certain, nevertheless limited, amount of organisms can be related to them (Kennedy and Southwood 1984) and because they contribute to forest structure. Therefore, they cannot be totally neglected. However, if their share increases and they start dominating the stand and outcompeting native species, they have a negative influence on biodiversity. Exotic tree species are taken into account provided that their proportional share in the total basal area or stem number is less than 5 percent. If their proportional share amounts to 5 to 50 percent, they are treated indifferently. An extra point is subtracted for each exotic species whose proportional share exceeds 50 percent. An analogous qualitative intervention is also applied by Hekhuis *et al.* (1994) and advised by Standovar (1997).

Large trees (40 ≤ dbh < 80 cm) create important niches for invertebrates, birds, mammals, fungi, and epiphytes, thus contributing to biodiversity. This contribution is even bigger for very large trees (dbh ≥ 80 cm). Very large trees normally occupy a larger growth area that automatically results in a limited number per sample plot. Both facts explain why large and very large trees are separately scored. In this case no distinction is made between indigenous and exotic tree species because tree size is a structural parameter making the identity of a species of minor importance.

The influence of natural regeneration of indigenous tree species on current biodiversity is probably rather limited. Regeneration diversity is mainly of interest for future biodiversity. However, because of its sensitivity for silvicultural measures, it is an important parameter for evaluating the impact of forest management on future biodiversity (Bradshaw and Lindén 1997).

Variation in stem diameter and the occurrence of different succession stages in a forest stand are often associated with a high degree of biodiversity (Esseen *et al.* 1992). The standard deviation of stem diameter is an important mean to express this variation (Bradshaw and Lindén 1997). The calculations are performed for trees with dbh ≥ 7 cm.

Herbal Layer

Diversity and degree of rareness of vascular plants, diversity of non-epiphytic bryophytes, and proportional cover of both are used as indicators of biodiversity for the herbal layer.

Many vascular plants specifically host certain specialized animal species, so that floral diversity is considered to have a major impact on faunal diversity. Plants are also very sensitive to silvicultural measures influencing biodiversity. They are easy to inventory and identify, which makes them suitable to serve as indicators. The Flemish flora consists of 1,279 vascular plants species of which 310 are confined to the socioecological group of "forest plants" (Cosyns *et al.* 1994, Stieperaere and Fransen 1982). However, due to the occurrence of different habitats within a forest, this number can increase significantly (Hermy *et al.* 1996). Therefore, plants that are not restricted to closed forest situations and that contribute to biodiversity cannot be ignored. Thus, all plants are treated alike for determining and scoring floral diversity.

The pure quantitative approach for determining floral diversity is supplemented by a qualitative aspect, which takes into account the degree of rareness of all plants. This is especially important for monitoring purposes towards evaluation of forest management in the framework of nature conservation. The degree of rareness is based on the occurrence of a species in a georeferenced grid of 4 x 4 km using a logarithmic frequency distribution (Stieperaere and Fransen 1982). According to its occurrence, each species receives a preliminary score (table 2). The preliminary scores of all species in a sample plot are added and scored a final time considering the classification given in appendix 1.

Table 2.—*Preliminary scoring of plant species according to their proportional occurrence in a 4-* x *4-km grid*

Proportional occurrence in a 4- x 4-km grid	Preliminary score
Percent	
< 1.38	8
1.38-10	5
10-23.97	2
23.97-48.97	1
> 48.97	0

Bryophytes also contribute to biodiversity and react even faster to changing environmental conditions than vascular plants (Biernath and Roloff 1993, Roloff and Stetzka 1995). Non-epiphytic bryophyte diversity per area unit is usually smaller than vascular plant diversity. The maximum score is therefore set to a smaller number of bryophyte species.

Spatial variation in proportional cover of the herbal layer contributes to biodiversity (Bradshaw and Lindén 1997). A cover of 50 percent theoretically offers the biggest chance for maximum variation. Chances for equal variation are the same for covers of 25 and 75 percent. Because the latter is usually related to an increased biomass, it scores higher. Plant biomass plays an important role in the food chain of an ecosystem, thus influencing diversity.

Deadwood

The importance of deadwood for conservation of biodiversity in forest ecosystems is generally acknowledged (Albrecht 1991, Detsch *et al.* 1994, Eckloff and Ziegler 1991, Kirby and Drake 1992, Möller 1994, Packam *et al.* 1992, Rabl 1993, Samuelsson *et al.* 1994). The importance of deadwood quantity, occurrence, size and shape diversity, and status of decomposition are stressed in relation to specialized invertebrates, fungi, and cavity-nesting animals (Altenkirch 1988, Ammer 1991, Barkman *et al.* 1983, Hodge and Peterken 1998, Komdeur and Vestjens 1983, Mabelis 1983, Rauh 1993, Schales 1992, Speight 1989). Snags and logs create different niches to which certain organisms are adapted, and are therefore treated separately in this study. From the available data in the state forest inventory, it is possible to calculate basal area, number of large trees, standard deviation of dbh of the snags, and total stem length and number of diameter classes of the logs. The identity of deadwood is not included, although its influence on certain faunal and floral aspects was determined (Hilt 1992, Stevens 1986). This influence decreases as the decomposition process continues (Palm 1959, Rauh 1993). Moreover, identification of deadwood is not always possible in the field.

The amount of standing deadwood is expressed in absolute units of basal area (square meters per hectare) instead of its proportional share in the total basal area of a forest stand. This is in order to avoid, for example, the possible false impression of an increased amount of deadwood after thinning a stand (without cutting the deadwood).

Large snags (dbh ≥ 40 cm) are monitored separately because they are usually associated with a high diversity of sizes and shapes creating different niches. Their large size offers opportunities for numerous rare species (Hekhuis *et al.* 1994, Rauh 1993, Siitonen and Martikainen 1994). Because of their importance, the occurrence of a single snag receives a high score.

The standard deviation of stem diameter is an important mean to express the variation in size of standing deadwood. As for the living aspect of the woody layer, the calculations are performed for trees with dbh ≥ 7 cm.

The amount of lying deadwood is limited to the occurrence of large logs (∅ ≥ 40 cm) and expressed as the total estimated stem length. Because of their importance to biodiversity, the occurrence of a cumulated stem length of 1 to 10 m receives a high score.

The diameter classes of the logs are the same as those used in the state forest inventory. These classes are used to indicate variation in lying deadwood. The occurrence of class 4 with the largest logs is rewarded with an extra point.

CASE STUDY

The biodiversity index is calculated for two types of data sets to check if the index reflects site and structural variability of forests in Flanders and if it is sensitive enough to indicate changes for monitoring purposes. The first data set includes 20 sample plots covering the major variability of forest stands and sites in Flanders. The second data set is confined to one forest and covers 10 forest stands with different structure and composition but with similar site conditions.

The forest stands of the first data set range from young homogeneous pine plantations to old mixed deciduous forests with a rich forest structure and species composition (table 3). The calculated biodiversity indexes reflect this variability in a logical way, ranking them in an increasing order. The difference between extreme values

Table 3.—*General description and intermediate scores of the different forest stands (encoded) of data set one and two*

				Scores		
Forest stand	**Description**	**Forest structure**	**Woody layer**	**Herbal layer**	**Dead wood**	**Total**
Dataset 1:						
Zoniën13	old Beech stand mixed with oak	16	12	11	9	48
Zoniën1	old Beech stand	18	13	7	8	46
Meerdaal7	old oak stand mixed with Hornbeam/Sycamore	18	14	11	3	46
Parike1	mature poplar stand	18	10	11	6	45
Neigembos5	old Beech stand mixed with oak/Ash	16	12	9	3	40
Zoniën27	old mixed stand of Beech, oak and Ash	16	6	11	3	36
84097	relatively old alder stand	17	4	13	2	36
178132	young birch stand	14	3	13	5	35
Neigembos6	young Ash stand mixed with alder/willow	18	4	13	0	35
Neigembos4	old Beech stand mixed with oak	14	11	5	5	35
317103	very young oak stand mixed with chestnut	11	3	13	4	31
257003	young, open homogeneous Scots pine stand	10	6	10	5	31
318113	young homogeneous oak stand	6	1	13	2	22
Jagersborg24d	young stand with Scots/Corsican pine clusters	10	2	8	2	22
318018	young homogeneous Corsican pine stand	6	2	6	7	21
95120	young homogeneous Scots pine stand	6	2	10	3	21
Pijnven4	relatively young homogeneous Red oak stand	9	6	5	0	20
Pijnven50	relatively young homogeneous Scots pine stand	9	2	6	2	19
251081	relatively old Corsican pine stand	6	2	5	4	17
95053	young homogeneous Scots pine stand	6	1	8	2	17
Dataset 2:						
Koeimook7	old Scots pine stand mixed with birch/oak	18	6	7	5	36
Koeimook5	relatively old birch stand mixed with oak	18	4	6	6	34
Koeimook9	old Scots pine stand	9	5	9	11	34
Koeimook10	old Scots pine stand mixed with birch	16	3	7	7	33
Koeimook8	old Scots pine stand	12	6	7	6	31
Koeimook6	relatively old birch stand mixed with oak	13	2	9	5	29
Koeimook4	young birch stand mixed with Alder buckthorn	14	4	6	5	29
Koeimook1	old Scots pine stand	12	5	5	5	27
Koeimook2	young homogeneous Beech stand	11	6	4	0	21
Koeimook3	relatively old homogeneous Corsican pine stand	7	4	7	0	18

amounts to 1/3 of the maximum score, leaving enough space for sound distinctions of biodiversity status between stands. None of the stands reach half of the maximum score, nor is the intermediate score for the four major indicators (forest structure, woody and herbal layers, and deadwood) systematically high (table 3). This indicates that none of the stands have reached a seminatural optimum so that the index may still significantly increase parallel to an improved stand development. The deadwood aspect, for example, is systematically low, indicating its inferior role in general forest management in the past.

One of the major disadvantages when using a biodiversity indicator system for temperate forests in western Europe is the lack of relicts of natural forest stands serving as reference for the different forest types. Data set two allows the investigation of a potential maximum score of the biodiversity index, because it includes young planted homogeneous stands as well as relatively old semi-naturally developed mixed stands on the same site. Table 3 illustrates that the score for human-made forest stands like Koeimook3 and Koeimook2 can potentially increase to the level of stands like Koeimook5 and Koeimook7, which were able to develop spontaneously, resulting in a species composition and forest structure probably approaching the natural situation. A difference of almost 20 points between these stands indicates a sensitivity of the index that is useful for monitoring purposes. Koeimook5 and Koeimook7 only resemble the natural situation so that their score is not the absolute maximum and can still increase. Due to site conditions, this absolute maximum will probably be lower in comparison with richer sites. Sensitivity of the index for monitoring purposes can be tested for other forest sites in the same manner. Since the data are georeferenced and digital soils maps are available, separate index calculations and thus biodiversity monitoring for different soil types are possible.

CONCLUSION

The score system for calculating the biodiversity index proves to be simple and easy to use. From a practical point of view, the system qualifies as a Biodiversity Evaluation Tool (BET) according to the criteria presented by the new European project aiming at developing indicators for biodiversity in European forests (BEAR 1998). The suggested stand-scale forest biodiversity index combines biological and structural indicators, based on available data from the state forest inventory. This strategy allows an immediate application on the level of the Flemish region without the need for extra measurements. A major disadvantage of this strategy is the limitation on including other potentially valuable indicators. Due to a general lack of detailed knowledge, the indicator choice is based on widely accepted assumptions of increased species richness in relation to a more varied and complex forest structure. However, the creation of new niches does not always guarantee that they will be filled in by the expected organism. All depends on colonization processes, which are linked to the occurrence of relict populations, species mobility, and isolation. Therefore, the index will serve as a monitoring tool to evaluate the impact of forest management on potential biodiversity rather than on biodiversity itself. The lack of references on natural forest structure and species composition and the fact that other important biodiversity indicators like forest history, connectivity, forest area, and site conditions are not taken into account limit its use to monitoring purposes. Therefore, the index is not meant to judge different forests on their biodiversity status and certainly not sufficient to compare forests on their value for nature conservation, due to its emphasis on the quantitative aspect of biodiversity. The suggested stand-scale forest biodiversity index can, however, be recommended as a provisional Biodiversity Evaluation Tool for developing forest stand management in strongly anthropogenically influenced forest landscapes.

ACKNOWLEDGMENTS

The authors thank the following people for reviewing this manuscript: Tor-Björn Larsson, Swedish Environmental Protection Agency, Stockholm, Sweden; Richard Bradshaw, Geological Survey of Denmark and Greenland (GEUS), Copenhagen, Denmark; and Tibor Standovár, Eötvös Loránd University, Budapest, Hungary.

LITERATURE CITED

Albrecht, L. 1990. Grundlagen, Ziele und Methodik der waldökologischen Forschung in Naturwaldreservaten. Naturwaldreservate in Bayern. Schriftenreihe, Band 1. München: Bayerisches Staatsministerium für Ernährung, Landwirtschaft und Forsten. 221 p.

Albrecht, L. 1991. Die Bedeutung des toten Holzes im Wald. Forst. Cbl. 110: 106-113.

Altenkirch, W. 1988. Naturschutz im Wirtschaftswald: Bemerkungen aus zoologischer Sicht. AFZ. 43: 684-686.

Ammer, U. 1991. Konsequenzen aus den Ergebnissen der Totholzforschung für die fortsliche Praxis. Forstw. Cbl. 110: 149-157.

Alho, J.; Kangas, J.; Kolehmainen, O. 1996. Uncertainty in the expert predictions of the ecological consequences of forest plans. Applied Statistics. 45: 1-14.

Barkman, J.J.; Doing, H.; Segal, S. 1964. Kritische Bemerkungen und Vorschläge zur quantitativen Vegetationsanalyse. Acta Botanica Neerlandica. 13: 394-419.

BEAR (Biodiversity Indicators of European Forests). 1998. EU FAIR Concerted Action presented at http://www.algonet.se/~bear.

Biernath, M.; Roloff, A. 1993. Ökologische Zeigerwerte für die wichtigsten Waldbodenmoose. Forstarchiv. 64: 9-16.

Bradshaw, R.H.W.; Lindén, M. 1997. RENFORS. Regeneration of natural forest stands for timber production and environmental value. EU progress report. Contract FAIR1-95-0420. 35 p.

Braun-Blanquet, J. 1951. Pflanzensoziologie. Grundzüge der Vegetationskunde. 2. Wien: Aufl. Springer. 631 p.

Christensen, M.; Emborg, J. 1996. Biodiversity in natural versus managed forest in Denmark. Forest Ecology and Management. 85(1-3): 47-51.

Cosyns, E.; Leten, M.; Hermy, M.; Triest, L. 1994. Een statistiek van de wilde flora van Vlaanderen. Vrije Universiteit Brussel, Instituut voor Natuurbehoud. 25 p.

Dalkey, N.; Helmer, O. 1962. An experimental application of Delphi method to the use of experts. Management Science. 9: 458-476.

Detsch, R.; Kölbel, M.; Schulz, U. 1994. Totholz - vielseitiger Lebensraum in naturnahen Wäldern. AFZ. 11: 586-591.

Dudley, N. 1996. Authenticity as a means of measuring forest quality. Biodiversity Letters. 3: 6-9.

Eckloff, W.; Ziegler, W. 1991. Über der Wert toter Baüme in der Waldlebensgemeinschaft. Forstarchiv. 62: 105-107.

Esseen, P.-A.; Ehnström, B.; Ericson, L.; Sjöberg, K. 1992. Boreal Forests-the focal habitats of Fennoscandia. In: Hansson, L., ed. Ecological principles of nature conservation. London: Elsevier: 252-325.

EWGRB (European Working Group on Research and Biodiversity). 1997. Understanding Biodiversity. An agenda for research into Biodiversity. Presented on the European Working Group on Research and Biodiversity EWGRB homepage http://www.oden.se/~ewgrb and submitted for printing to the Commission of the European Communities. Directorate-General XII for Science, Research and Development (Catizzone, M.; Larsson. T-B.; Svensson, L., eds.). 122 p.

Franklin, J.F. 1988. Structural and functional diversity in temperate forests. In: Biodiversity. Washington: National Academy Press: 166-175.

Hekhuis, H.J.; de Molenaar, J.G.; Jonkers, D.A. 1994. Het sturen van natuurwaarden door bosbedrijven. Een evaluatiemethode voor multifunctionele bossen. IBN-rapport 078, Wageningen: ibn-dlo. 146 p.

Helmer, W. 1987. Vleermuizen en bosstructuur. Nederlands Bosbouwtijdschrift. 59(11): 366-372.

Hermy, M.; Van Den Bremt, P.; Tack, G.; Coppin, P.; Gulinck, H. 1996. De ontwikkeling van de kennis van de flora van het Bos t'Ename. Dumortiera. 64-65: 35-44.

Hilt, M. 1992. Besiedlung von Fichten- und Eichentotholz durch Insekten. Vergleichende Untersuchungen an Käfern (Coleoptera) und Zweiflüglern (Diptera) im Allacher Forst (Forstamt Munchen). Köln: Universität Köln. 141 p. Diplomarbeit

Hodge, S.J.; Peterken, G.F. 1998. Deadwood in British forests: priorities and a strategy. Forestry. 71(2): 99-112.

Kangas, J.; Karsikko, J.; Laasonen, L.; Pukkala, T. 1993. A method for estimating the suitability function of wildlife habitat for forest planning on the basis of expertise. Silva Fennica. 27(4): 259-268.

Kennedy, C.E.J.; Southwood, T.R.E. 1984. The number of species of insects associated with British trees: a re-analysis. Journal of Animal Ecology. 53: 455-478.

Kirby, K.J.; Drake, C.M., eds. 1992. Deadwood matters: the ecology and conservation of saproxylic invertebrates in Britain. English Nature Science 7. Peterborough: English Nature. 105 p.

Köhl, M. 1996. Assessing and monitoring forest biodiversity in Switzerland and Germany. In: Bachmann, P.; Kuusela, K.; Uuttera, J., eds. EFI Proceedings N° 6. Joensuu: EFI: 95-104.

Komdeur, J.; Vestjens, J.P.M. 1983. De betekenis van dood hout voor de avifauna. Nederlands Bosbouw Tijdschrift: 86-90.

Mabelis, A.A. 1983. De betekenis van dood hout voor ongewervelde dieren. Nederlands Bosbouwtijdschrift: 78-85.

MacArthur, R.H.; MacArthur, J.W.; Preer, J. 1962. On bird species diversity II. Prediction of bird census from habitat measurements. American Naturalist. 96: 167-174.

Mitchell, P.L.; Kirby, K.J. 1989. Ecological effects of forestry practices in long-established woodland and their implications for nature conservation. O.F.I. Occas. Pap. 39. Oxford Forestry Institute, Department of Plant Sciences, University of Oxford.

Möller, G. 1994. Alt- und Totholzlebensräume. Ökologie, Gefährdungssituation, Schutzmaßnahmen. Beiträge für Fortswirtschaft und Landschaftökologie. 28(1): 7-15.

Nilsson, S.G.; Arup, U.; Baranowski, R.; Ekman, S. 1995. Tree-dependent lichens and beetles as indicators in conservation forests. Conservation Biology. 9: 1208-1215.

Noss, R.F. 1990. Indicators for monitoring biodiversity: a hierarchical approach. Conservation Biology. 4(4): 355-364.

Oliver, I.; Beattie, A.J. 1996. Designing a cost-effective invertebrate survey: a test of methods for rapid assessment of biodiversity. Ecological Applications. 6: 594-607.

Otte, J. 1989. Ökologische Untersuchungen zur Bedeutung von Windwurfflächen für die Insektenfauna. Teil I & II. Waldhygiëne. 17: 193-247. 18: 1-36.

Packam, J.R.; Harding, D.J.L.; Hilton, G.M.; Stuttard, R.A. 1992. Functional ecology of woodlands and forests. London: Chapman and Hall. 407 p.

Palm, T. 1959. Die Holz- und Rindenkäfer der Süd- und Mittelschwedischen Laubbäume. Opuscula Entomologica, (Lund) Supplement XVI. 1-374.

Peterken, G.F. 1996. Natural woodland: ecology and conservation in northern temporate regions. Cambridge: Cambridge University Press. 522 p.

Pukkala, T.; Kangas, J.; Kniivilä, M.; Tiainen, A.-M. 1997. Integrating forest-level and compartment-level indices of species diversity with numerical forest planning. Silva Fennica. 31(4): 417-429.

Rabl, K. 1993. Totholz - wichtiger Teil im forstlichen Ökosystem. Österreichische Forstzeitung. 12.

Rauh, J. 1993. Faunistisch-ökologische Bewertung von Naturwaldreservaten anhand repräsentativer Tiergruppen. Naturwaldreservate in Bayern. Schriftenreihe, Band 2. München, Bayerischen Staatsministeriums für Ernährung , Landwirtschaft und Forsten. 199 p.

Roloff, A.; Stetzka, K.M. 1995. Waldbodenmoose als Zeigerpflanzen und Bioindikatoren - Erkennen, Bestimmen, Nutzen. Forst und Holz. 50(20): 635-642.

Rune, F. 1997. Naturkvalitet i skov. Statusrapport. Indikatorer for naturkvalitet. Identifikation og testning af indikatorer for naturkvalitet i udvalgte terrestriske naturtyper. Forskningcentret for Skov & Landskab. 36 p.

Samuelsson, J.; Gustafsson, L.; Ingelög, T. 1994. Dying and dead trees: a review of their importance for biodiversity. Swedish Environmental Protection Agency report series. Rep. 4306. Uppsala: Swedish Threatened Species Unit. 109 p.

Schales, M. 1992. Totholz: Ein Refugium für seltene Pilzarten. AFZ. 20

Schuck, A.; Parviaenen, J.; Bücking, W. 1994. A review of approches to forestry research on structure, succession and biodiversity of undisturbed and semi-natural forests and woodlands in Europe. European Forest Institute Working Paper 3.

Siitonen, J.; Martikainen, P. 1994. Occurence of rare and threatened insects living on decaying *Populus tremula*: a comparison between Finnish and Russian Karelia. Scandanavian Journal of Forest Research. 9: 185-191.

Southwood, T.R.E. 1961. The number of species of insect[s] associated with various trees. Journal of Animal Ecology. 30: 1-8.

Speight, M. 1989. Saproxylic invertebrates and their conservation. Nature and Environ. Ser. 42. Strasbourg: Council of Europe. 81 p.

Standovar, T. 1997. Comments on using diversity in assessing forest naturalness. Naturalness and European Forests. International Congress. Programme and abstracts. Strasbourg: Council of Europe.

Stevens, G. 1986. Dissection of the species-area relationship among wood-boring insects and their host plants. American Naturalist. 128(1): 35-45.

Stieperaere, H.; Fransen, K. 1982. Standaardlijst van de Belgische vaatplanten, met aanduiding van hun zeldzaamheid en socio-ecologische groep. Dumortiera. 22: 1-41.

Van Den Meersschaut, D.; Lust, N. 1994. Bosbouw. In: Verbruggen, A., ed. Leren om te keren. Milieu- en natuurrapport Vlaanderen. Leuven: Garant. Vlaamse Milieumaatschappij: 75-82.

Waterinckx, M.; Haelvoet, P. 1997. Operationaliseren en begeleiden van de uitvoeringsfase van de bosinventarisatie van het Vlaamse Gewest. Eindverslag. Afdeling Bosbeheer en Ruimtelijke Informatietechnieken. Universiteit Gent. 117 p.

Appendix 1.—*Detailed overview of the score system for calculating the biodiversity index.*

Forest Structure

CANOPY CLOSURE	Score
> 2/3 of the area	2
1/3-2/3 of the area	4
< 1/3 of the area	3

STAND AGE *Years*	
1-60	1
61-100	2
101-160	5
> 160	7
Uneven aged	5

NUMBER OF STOREYS	
1	2
> 1	4

SPATIAL TREE SPECIES MIXTURE	
homogeneous	1
clustered	3
individual	5

Woody Layer

NUMBER OF TREE SPECIES	Score
1-2	1
3-4	2
5-6	3
7-8	4
> 8	5

NUMBER OF LARGE TREES	
1-5	1
6-10	2
11-15	3
16-20	4
> 20	5

NUMBER OF VERY LARGE TREES	
1	3
2-3	4
≥ 4	5

NATURAL REGENERATING SPECIES	
1-4	1
5-8	2
9-12	3
> 12	4

STANDARD DEVIATION OF DBH *Centimetres*	
10-15	1
16-20	2
21-25	3
26-30	4
31-35	5
> 35	6

Herbal Layer

NUMBER OF PLANT SPECIES	Score
1-5	1
6-10	2
11-15	3
16-20	4
21-25	5
26-30	6
31-35	7
36-40	8
41-45	9
> 45	10

DEGREE OF RARENESS	
1-5	1
6-10	2
11-15	3
16-20	4
21-25	5
26-30	6
> 30	7

NUMBER OF BRYOPHYTES	
1-5	1
6-10	2
11-15	3
16-20	4
> 20	5

TOTAL COVER *Percent*	
6-25	1
26-50	2
51-75	3
> 75	1

Deadwood

SNAGS

BASAL AREA *Square metres per hectare*	Score
< 2	1
2-3.5	2
3.6-5	3
> 5	4

NUMBER OF LARGE TREES	
1	3
2-3	4
≥ 4	5

STANDARD DEVIATION OF DBH *Centimetres*	
10-15	1
16-20	2
21-25	3
26-30	4
31-35	5
> 35	6

LOGS

STEM-LENGTH LARGE TREES *Metres*	
1-10	3
11-20	5
> 20	7

NUMBER OF DIAMETER CLASSES	
1	2
2	4
3	6
4	8

Measurement Consistency in Natural Resources Inventories

Digital Terrestrial Photogrammetric Methods for Tree Stem Analysis

Neil A. Clark, Randolph H. Wynne, Daniel L. Schmoldt, and Matt Winn

Abstract.—A digital camera was used to measure diameters at various heights along the stem on 20 red oak trees. Diameter at breast height ranged from 16 to over 60 cm, and height to a 10-cm top ranged from 12 to 20 m. The chi-square maximum anticipated error of geometric mean diameter estimates at the 95 percent confidence level was within ± 4 cm for all heights when obtained at a distance of 12 m or greater. Error increased with increased stem height from ± 3 to ± 7 cm for heights from 1 to 20 m. In general, the error is equivalent to three times the instrument precision, which varies with distance. Two-thirds of the volume estimates were within 8 percent of "actual" volumes.

Diversifying values and increased accountability are forcing today's natural resource managers to make complex and defensible decisions. Information requirements to make these decisions are expanding in magnitude and variety, especially in forestry. Multiple resource inventories are being developed to maximize the efficiency of data collection for multiple objectives (Lund 1998). Analyses involving the health, volume, growth, change, and potential of forest resources at some level require information about individual stems. Collecting the large amounts of data required for these purposes is slow and expensive. In this paper, a method is set forth using a non-metric digital camera to capture raw data from an individual stem that can later be used for customized analysis. Diameter and height measurements were derived in this study to examine the effectiveness of this method for determining stem volume.

CAMERA INFORMATION

The camera falls into the optical fork (Grosenbaugh 1963) category of optical dendrometers, which are devices that allow measurements to be taken visually from a remote location. With optical forks, two lines of sight passing through two tangential points on the tree stem representing the diameter and intersecting at a point in front of "the observer" are used to determine an angle. This angle is scaled using the distance to the point of measurement (range) to determine the stem's diameter. "The observer" in respect to the camera is the image plane, and the point of intersection is the focal point of the lens.

In conventional photography, the image plane consists of an area of film coated with a light-sensitive emulsion. In the case of the Kodak DC120™ digital camera, this image plane takes the form of an 850 x 984 element CCD (charge-coupled device) array that produces a resultant image that is 960 x 1,280 image pixels in dimension (Kodak 1997). Each element in the DC120 CCD array is 7.8 x 5.0 microns in dimension (Kodak 1997). These 836,400 packets are then transformed to produce the final 3,686,400 digital output values (1,280 x 960 (pixels) x 3 (colors)). Although the size of the CCD elements was reported, the image pixel size had to be empirically derived since the details of the interpolation algorithms are proprietary. The procedure used to do this can be found in *Clark et al.* (1998). The resultant image pixel dimension was found to be 5 microns.

The image processing software used for image measurement did not allow for sub-pixel mensuration, so the precision of the camera can be defined as a linear function of the distance from the imaged object. Equations 1 and 2 were used, substituting 5 microns for *d*, 7 mm for *f*, and setting L_o at 1 m. Solving for D resulted in an object space precision in the horizontal and vertical directions of ± 0.7 mm per meter from the object (fig. 1).

$$s=\frac{d}{D} \tag{1}$$

$$s=\frac{f}{L_0} \tag{2}$$

where s = scale
d = image space distance
D = object space distance
f = focal length
L_o = horizontal distance from focal point to imaged object

Graduate Research Assistant and Assistant Professor of Forestry, respectively, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA; and Research Forest Products Technologist and Forest Technician, respectively, USDA Forest Service, Southern Research Station, Blacksburg, VA, USA.

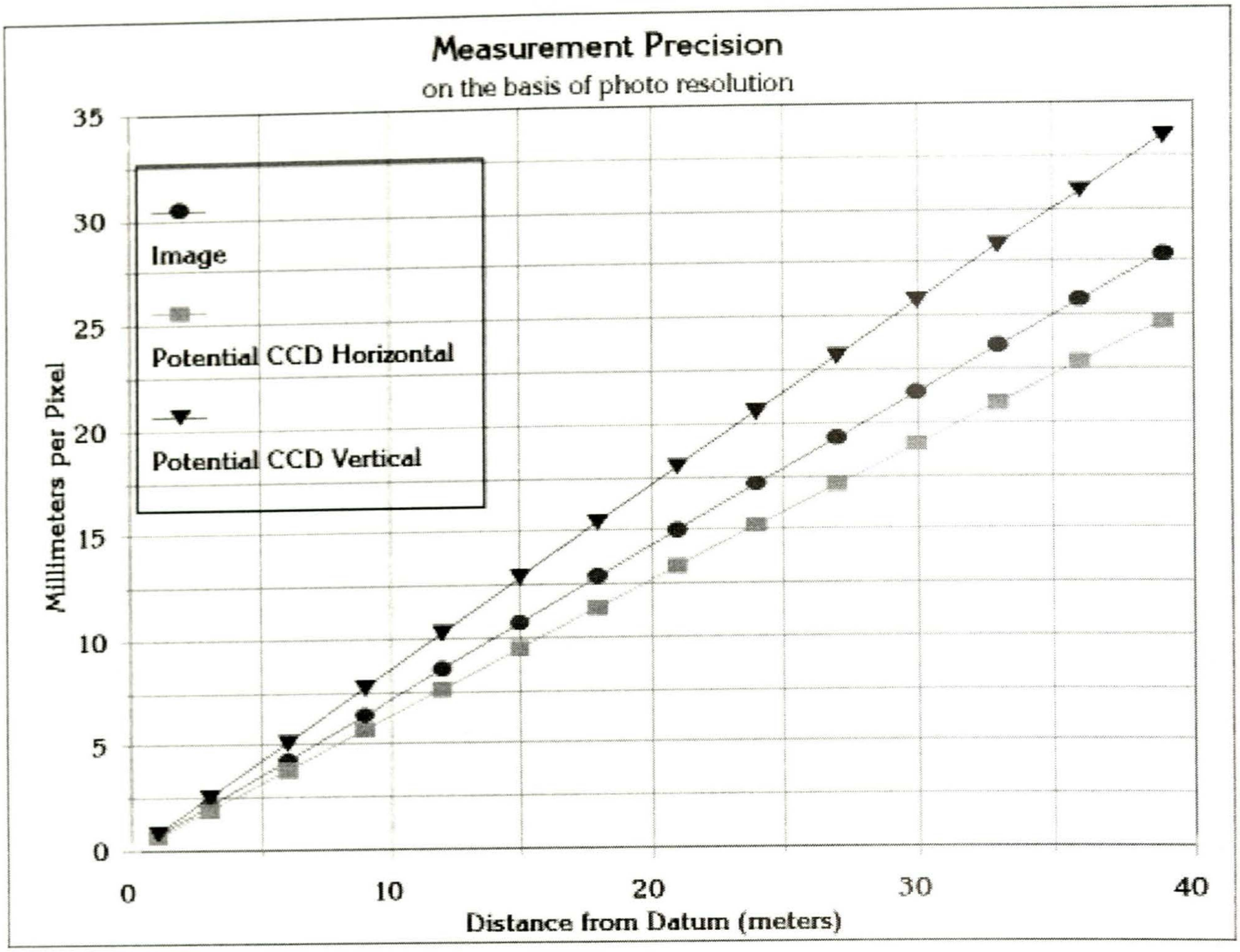


Figure 1.—*Measurement precision based on pixel size for the Kodak DC-120 digital camera. Resolution is calculated from the product of the pixel dimension and the distance of the focal point from the datum plane divided by the focal length of the camera. The focal length of the DC-120 set at maximum wide angle is 7 mm. Image pixel size is empirically determined to be 5 microns. Potential horizontal and vertical CCD "pixel" size is calculated from the product of the CCD element size (7.8 x 5.0 microns) and the array dimensions (850 x 984 pixels) and dividing by the image array dimensions (960 x 1,280). This calculation results in 4.4 and 6.0 micron "virtual pixel" vertical and horizontal dimensions, respectively. This is an estimate since the interpolative techniques are unknown.*

FIELD DATA INFORMATION

Stem Selection

Red oak (*Quercus spp.*) was selected for this study due to its moderate variations in bark and form distinctions. Northern red oak (*Quercus rubra*), black oak (*Quercus velutina*), and scarlet oak (*Quercus coccinea*) were the species sampled in this study. This species criterion was imposed to reduce variation due to morphological dissimilarity among species. Five stems were selected from each of four diameter strata, (16 - 30 cm), (31 - 45 cm), (46 - 60 cm), and (> 60 cm), to observe effects due to size. Two stems in each category were collected on a shallow-soiled ridgetop near Radford, VA; the remaining three stems were located on a moderately well drained midslope in Asheville, NC.

Image Collection Procedure

The DC120 features a 3x magnification, but the shortest focal length was used in this study to capture the maximum length of stem per image. Distance between the stem and the camera station was one of the main criteria investigated. Inversely related to this was the angle of inclination of the camera. To study the possible effects of this angle/distance relationship, data were captured at distances of 3, 6, 9, 12, and 15 m.

At each stem a quick visual survey was made to select four orthogonal directions with the least amount of obstruction from understory vegetation or parts of adjacent stems. Using red spray paint, a mark was made on one face of the stem corresponding with the direction determined from the visual survey. This mark was used as an indicator of the direction of the first camera station and aided in orientation of the caliper measurements after the stem was felled. The second camera station was directly opposite the mark, and the third and fourth camera stations were perpendicular to the mark (fig. 2).

The camera was oriented with the widest dimension of the image plane in the vertical direction. The shortest focal length was used to capture the maximum amount of stem height per image. The shutter speed was set to auto-exposure + 1.5 stops for most images. In backlit conditions the exposure time was reduced, and conversely, in lower light conditions the exposure time was increased. The LCD monitor on the camera was used to view the image seconds after capture to determine if the exposure was correct. If it was not, the image was erased, exposure adjusted, and another image was acquired.

A nylon tape was secured at the stem's base at a right angle to the plane of the stem axis and the camera station (B_o) (fig. 3). After the camera was adjusted on the tripod so that this point was visible through the viewfinder, this distance was measured and recorded to the nearest 0.5 inch. A handheld clinometer was used to measure the inclination angle (θ) (fig. 3) to the nearest ± 5 percent slope, and this angle was recorded. Overlapping images were captured of the entire stem face before locating the antipodal camera station and repeating the process.

In Situ Data Collection

In situ data were collected to determine the accuracy of image-derived measurements. After all imagery was acquired, the stems were felled. Height measurements were made from the uphill contact point of the ground and stem. The downed stem was then measured with a nylon tape to determine the exact points at which to measure diameter. Steel calipers were used to measure diameters perpendicular to the camera station locations, resulting in two perpendicular measurements at each height (fig. 2). Therefore, one caliper measurement corresponds to two camera measurements for each directional diameter. Diameter measurements were taken at 1.4 m (diameter at breast height [dbh]) and every 1.2 m from the height of 2.4 m to a 10-cm top or to the end of the merchantable stem.

Office Procedure

Images were downloaded from the 10 megabyte removable storage card in the camera into a computer for processing using the Kodak Picture Transfer™ software that accompanied the camera. The images were transferred and stored in the native KDC format because this format also allows information such as the quality setting, exposure time, and date/time to be associated with each image. A TWAIN module provided with the camera was

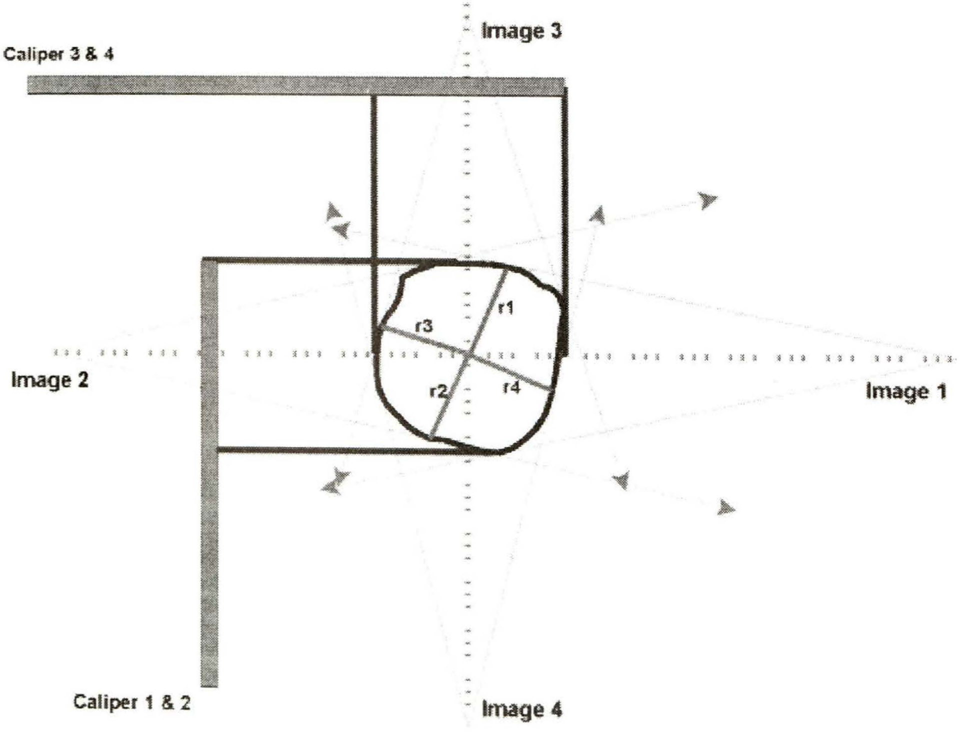


Figure 2.—*Orientation of caliper measurements and camera stations for the procedure used in this study.*

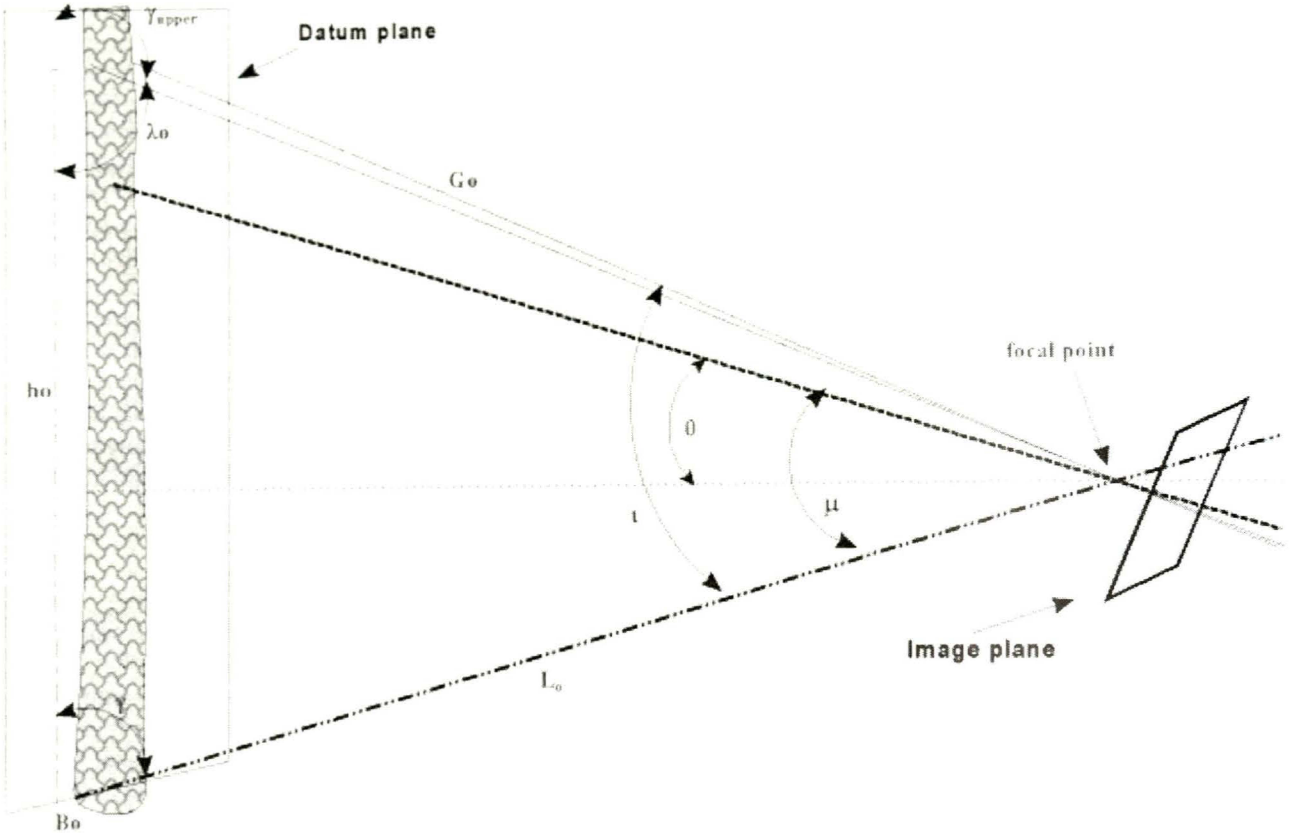


Figure 3.—*Diagram of object space showing measured or calculated angles, distances, and points.*

subsequently used to convert the images to tagged image file format (TIFF) as needed. The camera offers several quality settings that compress the image to varying levels in the camera. The quality setting number three used in this study has an approximate file size of 240 kilobytes, which expands to 3,686 kilobytes when completely uncompressed to the TIFF format.

The images were sequentially numbered by the camera in the order they were captured. Great care was taken to ensure that the images remained in the same queue so that they could be matched with the correct angle, distance, face, and stem field data. Image measurements in this study were obtained using the University of Texas Health Science Center at San Antonio free ImageTool[1] program. Ancillary data were entered into an ASCII file that was accessible to diameter extraction software written by the author[2].

For each image, tree number, face number, image distance (L_o), and angle of inclination (θ) were transferred from field data sheets into this ASCII file. The image of the stem's base was viewed, and the image row value representing B_o was transmitted to the ASCII file and assigned a height value (fig. 3). Given that this was the base point, it was adjusted or estimated so that 0 was the highest point where the ground met the stem. On level ground, it was possible that all four base images per stem could have been set to 0; otherwise, the uphill (the side where the tape was secured) side of the faces perpendicular to the slope was set equal to 0. Point B_o for the upslope and downslope images was determined by averaging the distance between the high and low sides of the images showing the slope and subtracting from 0.

A point (a) was selected that could be identified in both the upper and lower images to determine B_o and L_o for the upper image. After the row values for point a from each of the images and the B_o value of the lower image were entered, B_o and L_o for the upper image were calculated by a module in the diameter extraction software. This height was transferred to the ASCII file along with the corresponding row value from the upper stem image. B_o for the upper image becomes the identifiable point with height

---

[1] *Available from the Internet by anonymous FTP from* ftp://maxrad6.uthscsa.edu

[2] *Contact author at* neclark@vt.edu *for code or other information related to measurement derivation.*

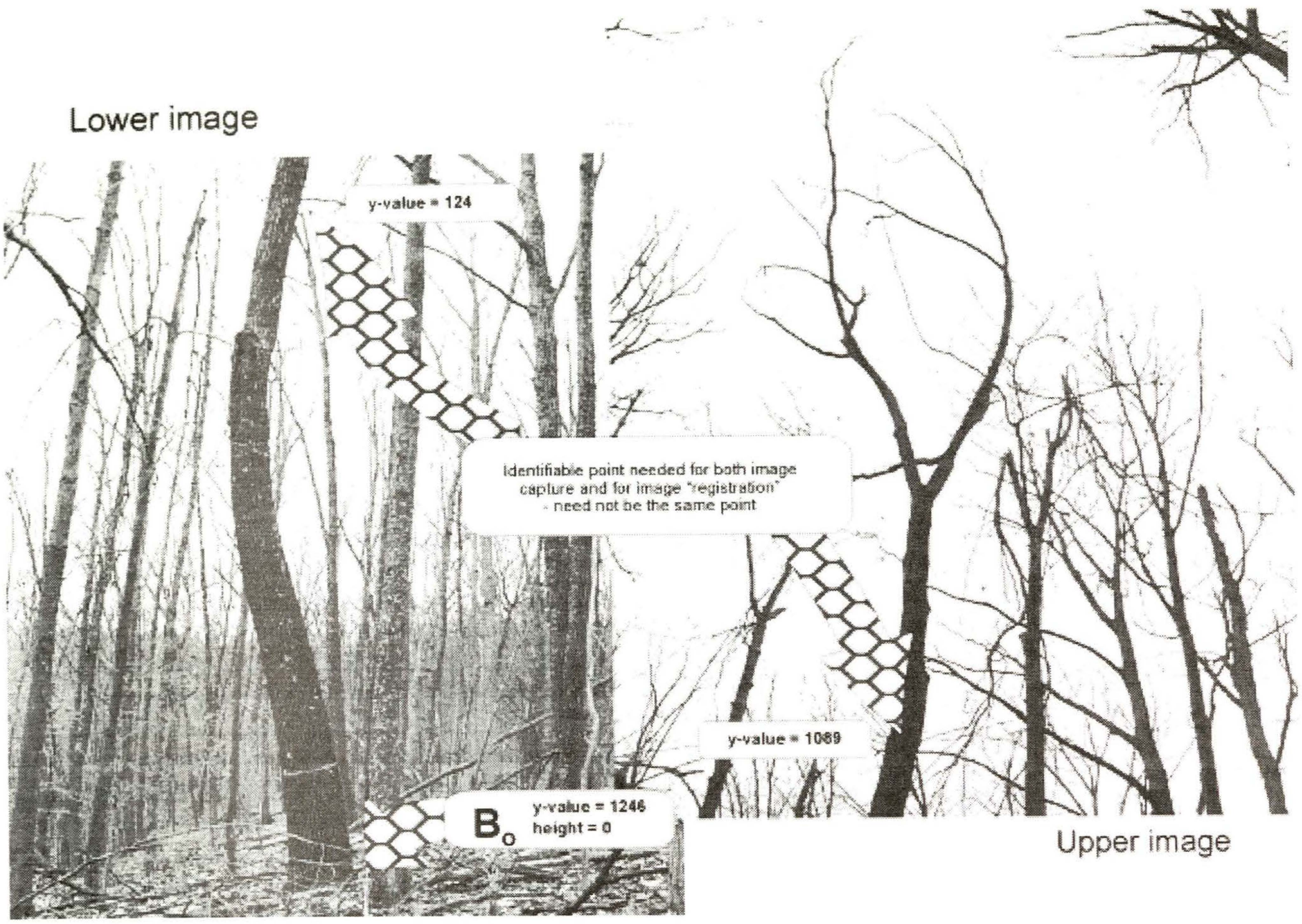

Lower image
y-value = 124
Identifiable point needed for both image capture and for image "registration" - need not be the same point
y-value = 1069
B_o
y-value = 1246
height = 0
Upper image

Figure 4.—*Upper and lower images at a single camera station showing location and image row value of* $\boldsymbol{B}_o$ *and identifiable point* ***a*** *and row values for each of the images.*

calculated from the lower image to *a*. L_o for the upper image becomes the distance from the focal point to *a*, and γ becomes 180° minus the angle formed by the stem axis and the ray between the focal point and *a* in the lower image.

Diameters were derived from the raw image data using the diameter extraction software. Tree numbers and stem heights of the desired diameters were entered into an ASCII file. The program reads the ASCII file containing the field data and image information and the stem and height ASCII file, and it outputs the names of the images that contain the points that correspond to the desired diameters and their corresponding row values. The image coordinates representing the left and right edges of the stem at the respective row value were obtained with the ImageTool program and imported to the diameter extraction software.

There were two caliper measurements of diameter for each height and four camera measurements of diameter for each height. The two diametrical camera measurements for the same distance from the tree were arithmetically averaged. From this, the two perpendicular measurements for the camera were used to calculate the geometric mean diameter (GMD) of a circle with the same area as an ellipse with axes *a* and *b* (Equation 3). GMD at each height was also calculated by this same method substituting the two caliper measurements for *a* and *b*.

$$GMD = 2\sqrt{ab} \tag{3}$$

where a and b = perpendicular directional diameters
GMD = geometric mean diameter

Cubic foot volume (later converted to cubic meters) was then calculated using Smalian's formula (Equation 4) for each 1.2-m (4-foot) bolt and summed to report the total merchantable volume for the stem. English units are used here for the convenience of comparison to existing volume tables.

$$Volume = \frac{\pi}{4 \times 144} \frac{D_l^2 + D_s^2}{2} l \qquad (4)$$

where D_l = large end diameter (inches)
D_s = small end diameter (inches)
l = length of section (feet)

Although Smalian's formula tends to overestimate volume, especially for the butt log, it serves only as a means of comparison rather than an accurate estimate of volume.

A chi-square test (Equation 5), such as introduced by Freese (1960) to determine whether a technique meets a certain accuracy requirement and modified by Bell and Groman (1971) to determine the maximum anticipated error, was used to measure the anticipated accuracies at the various distances and for different diameter classes.

$$E = \sqrt{\frac{\sum_{i=1}^{n} \left[\left(x_{i-\mu_i} \right)^2 \right] \bullet r^2}{X_n^2}} \qquad (5)$$

where x_i = camera estimate of the i^{th} observational unit
μ_i = "true" estimate of the i^{th} observational unit
r^2 = value of the standard normal deviate at a set α level
χ_n^2 = chi-square value with n degrees of freedom

RESULTS

Field Data

There were 241 paired perpendicular diameter measurements taken with the conventional. Varying stem heights, damage incurred during felling, and human error accounted for unequal sample sizes within the various strata. Table 1 shows the number of field measurements taken by height category.

Image Data

Table 1 also shows the numbers of geometric mean diameter estimates that were derived from the image measurements. Missing GMD's are the result of at least one of the four image measurements being absent. This occurred in cases where the stem was occluded by objects in the foreground to the extent that a confident measurement could not be obtained. This visibility concern can be avoided in non-experimental situations where there are fewer restrictions on camera station location and tree height designation. There were no great differences in measurement attainability from the 6- to the 15-m distance class. The 3-m distance numbers fall off sharply after about the 11-m stem height mark, predominantly due to the sensitivity of the acute viewing angle to stem lean.

Table 1.—*Number of field and image collected diameter measurements obtained from 20 red oak stems (8 in Radford, Virginia / 12 in Asheville, North Carolina) in March/April 1998*

	Nominal distance of camera station (m)					
Stem height (m)	**3**	**6**	**9**	**12**	**15**	**Field**
1.4	18	18	18	18	18	18
2.4	19	18	18	18	17	19
3.7	19	19	19	19	19	19
4.9	19	18	19	19	19	19
6.1	17	18	18	18	18	19
7.3	17	18	18	18	18	19
8.5	17	18	18	18	18	19
9.8	16	19	19	20	19	20
11.0	12	18	20	20	19	20
12.2	9	17	17	18	15	20
13.4	4	11	14	14	10	15
14.6	3	10	9	11	12	13
15.8	2	6	7	8	9	10
17.1	2	4	3	4	4	6
18.3	0	2	1	0	1	3
19.5	0	0	1	0	1	2
	174	214	219	223	217	241

Analysis of Variance Results

Analysis of variance for an experiment with repeated measures was performed on the data to examine the various effects. The procedure was run using the SAS proc mixed function (Littell *et al.* 1996). The 20 stems were classified into four diameters (breast height) classes - (16 - 30 cm), (31 - 45 cm), (46 - 60 cm), and (> 60 cm), each containing five stems. The distances of 3, 6, 9, 12, and 15 m were studied as fixed effect as well as height in 1.2-m increments (16 levels) beginning at 1.4 m from the ground. Because every stem was an experimental unit for each of the treatments, repeated measures tests were used to account for the effects of the subjects (stems). Orthogonal contrasts were examined to determine significant differences among the means. Several models were run to determine the significant effects that contribute to error using this technique. Distance, diameter class, height, and distance/height interaction were used as fixed effects in the models. There were no random effects.

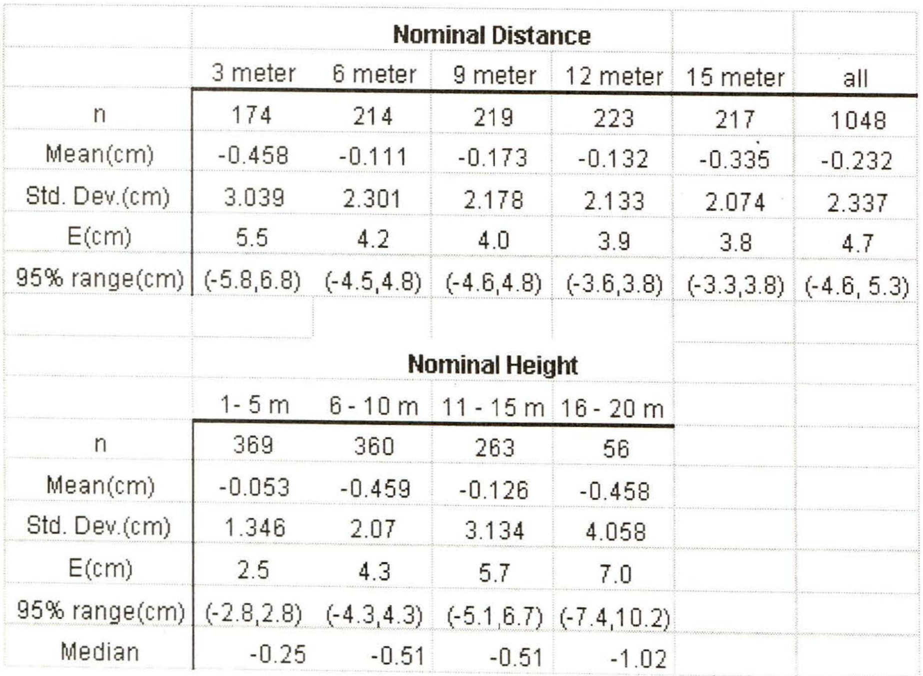
The first model that was run included all the factors. Only height and the interaction term showed significant effects at the 95 percent confidence level. All subsequent models examined each effect separately. The model using the nominal distance as the only effect did not show any significant differences at the 95 percent level. It can be noted, however, that the average deviation from zero at the 3-m distance was greater than at any other distance (table 2). The largest standard deviation was also at the 3-m distance.

Height was stratified into four classes—(1-5 m), (6-10 m), (11-15 m), and (16-20 m)—to see if the significant effect was simply due to the extreme level of stratification. The analysis of variance showed no significant differences among the means. Even though the equal variance assumption was ignored, it is apparent that the maximum difference between any of the means does not approach even the smallest standard deviation. Table 2 shows that the standard deviations of these observations rise about 1.5 cm for every 5 m increase in height. This variance difference is readily apparent in the scatterplots of the errors by height at various distances (fig. 4). Visual interpretation of these plots shows that in every case the variance increases with height. The errors at the 3-m distance are more dispersed than at any other distance. The 95 percent range results from the ordered difference results bring the magnitude of these results to light (table 2).

Volume Results

Volumes were calculated as previously described. Volumes were calculated for each of the 20 stems in each of the distances, regardless of missing camera observations. Where there were missing field observations, only the section of the stem measured in the field was compared. For example, if the 1.4-m distance was not

Table 2.—*Summary statistics for camera minus caliper geometric mean diameter estimates in centimeters by distance and diameter for 20 red oak stems. Reported are the arithmetic means and standard deviations, the maximum anticipated error (E) using the chi-square test for accuracy, and the actual measurement range of the nearest 95 percent of the observations from the median observation.*



	Nominal Distance					
	3 meter	6 meter	9 meter	12 meter	15 meter	all
n	174	214	219	223	217	1048
Mean(cm)	-0.458	-0.111	-0.173	-0.132	-0.335	-0.232
Std. Dev.(cm)	3.039	2.301	2.178	2.133	2.074	2.337
E(cm)	5.5	4.2	4.0	3.9	3.8	4.7
95% range(cm)	(-5.8,6.8)	(-4.5,4.8)	(-4.6,4.8)	(-3.6,3.8)	(-3.3,3.8)	(-4.6, 5.3)

	Nominal Height			
	1 - 5 m	6 - 10 m	11 - 15 m	16 - 20 m
n	369	360	263	56
Mean(cm)	-0.053	-0.459	-0.126	-0.458
Std. Dev.(cm)	1.346	2.07	3.134	4.058
E(cm)	2.5	4.3	5.7	7.0
95% range(cm)	(-2.8,2.8)	(-4.3,4.3)	(-5.1,6.7)	(-7.4,10.2)
Median	-0.25	-0.51	-0.51	-1.02

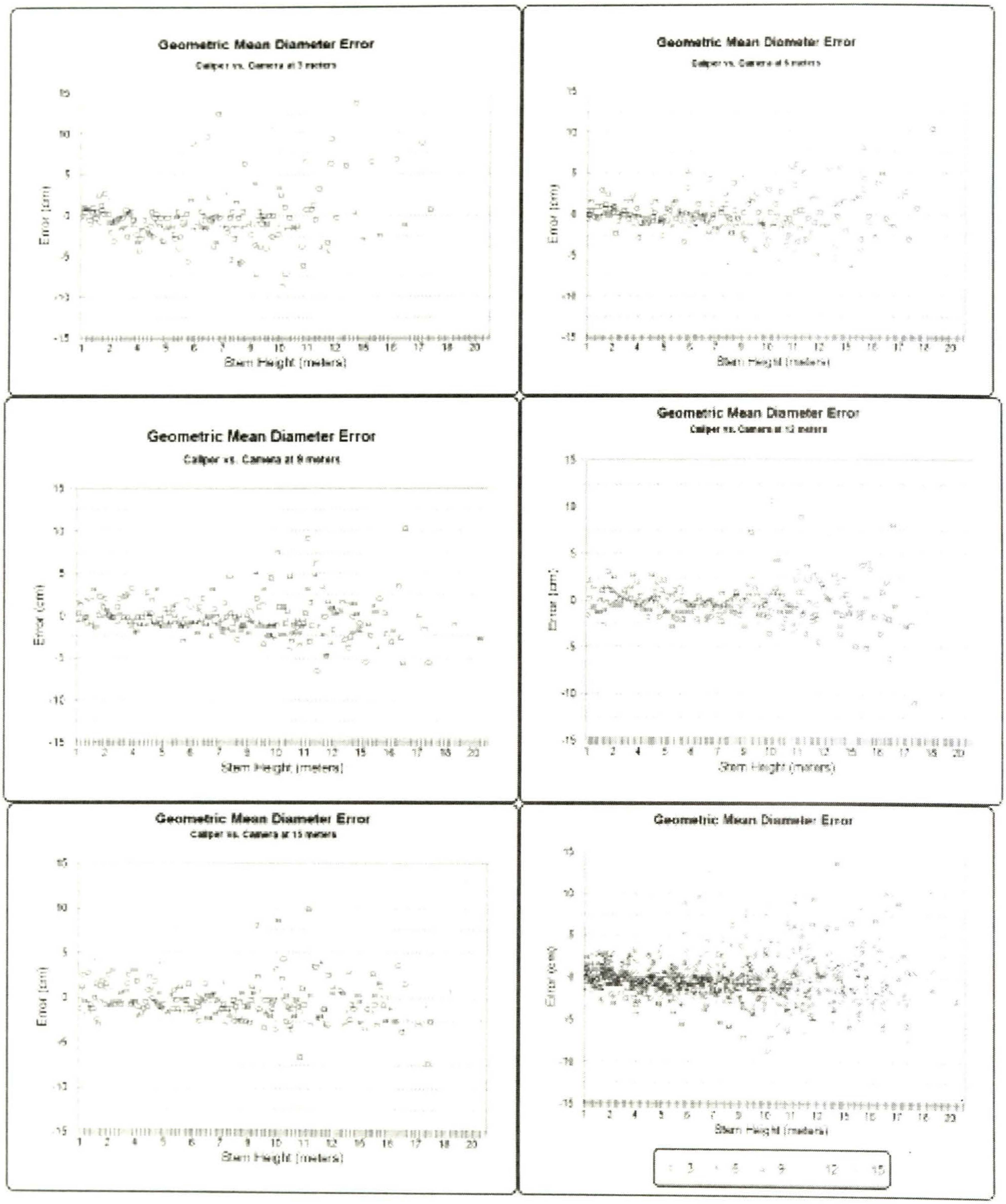


Figure 5.—*Scatterplots of geometric mean diameter error in centimeters by height for five distances from 3 to 15 m.*

recorded, only the stem section from 2.6 m to the measured top was evaluated for both camera and caliper. For the stem that split when felled, single caliper measurements were used up to 9.8 m. The GMD's were used when possible for the camera estimates, but directional diameters were used where the GMD's could not be calculated. Only distance was used as a factor since height is intrinsically related to volume and diameter was not found to have any significant effect. The 12-m distance resulted in the mean closest to zero and had the lowest standard deviation, although it is not significantly different from other distances in the 6- to 15-m range. The 3-m distance had the greatest standard deviation and also the largest difference of the mean from zero.

To better see the advantages of this system, the results were compared to results from an alternative method. The alternative method was using volume equations developed specifically for northern red oak in the southern Appalachian Mountains. The equations used (Equations 6 and 7) were for cubic foot volume, later converted to cubic meters, for wood and bark using dbh and height to a 4-inch top (10 cm) as independent variables (Clark and Schroeder 1986). This equation still requires an instrument to take upper stem measurements to obtain an estimate with any precision. For the comparison in this study, the GMD's from the caliper estimates were used along with the field-taped heights for equation input parameters. Because these are the same measurements used in "actual" volume calculations, any error comes from the model. Height to a 4-inch top was not acquired in the field for every tree. Diameter data were collected for some trees only up to the end of the merchantable stem. This is seen particularly in the larger diameter stems where the equations produce an underestimate of volume. For many of these stems without a clear dominant main stem, it is often difficult to determine which 4-inch top should be measured.

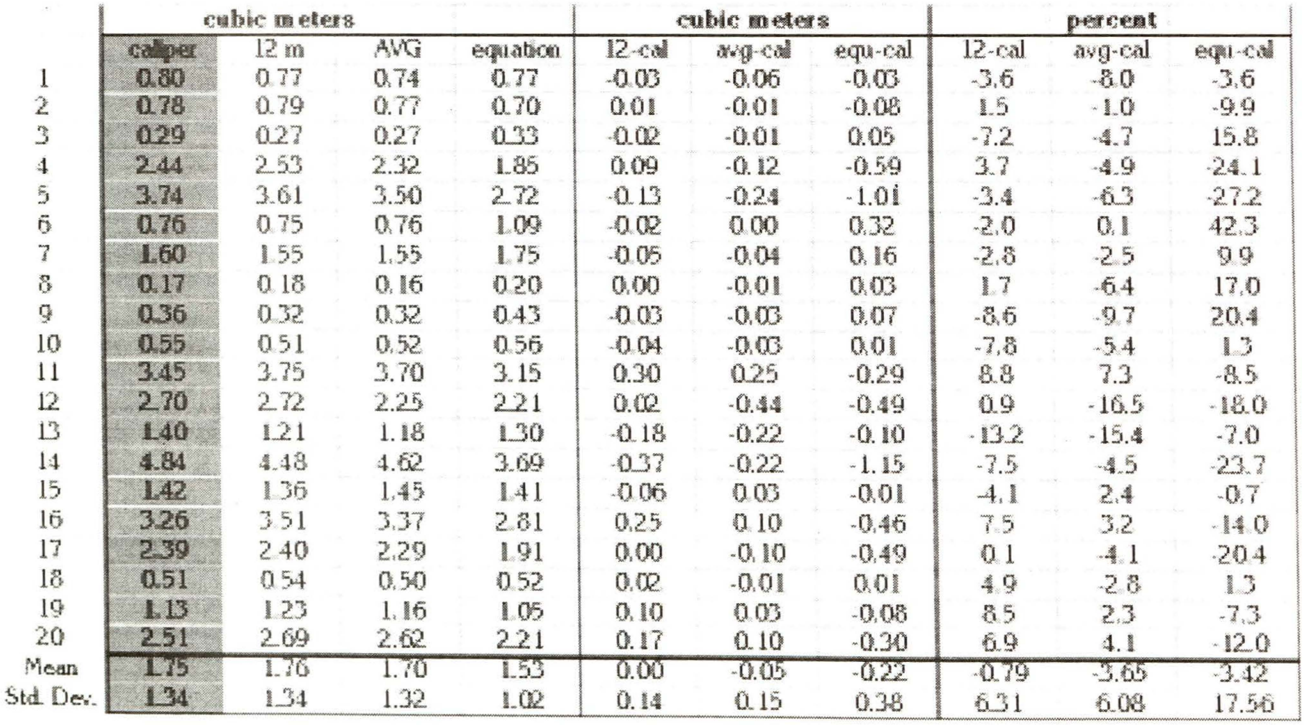
$$volume_{<11''} = 0.03592(d^2 h)^{0.73586} \qquad (6)$$

$$volume_{<11''} = 0.01199(d^2)^{0.95561} h^{0.73586} \qquad (7)$$

where $volume_{<11''}$ and $volume_{>11''}$ = cubic foot volumes of wood and bark for stems less than 11 inches and greater than 11 inches, respectively.
d = diameter at breast height in inches
h = height to a 4-inch top in feet

Although the equation provides quite an accurate assess-

Table 3.—*Volume estimates for 20 red oak stems comparing camera estimates from the 12 meter distance, the average of all camera estimates, and the equation estimates to the "true" caliper estimates. The left four columns show the stem volumes in cubic meters, the next three columns from the left show the cubic meter differences, and the final three columns report the percent differences.*



	cubic meters				cubic meters			percent		
	caliper	12 m	AVG	equation	12-cal	avg-cal	equ-cal	12-cal	avg-cal	equ-cal
1	0.80	0.77	0.74	0.77	-0.03	-0.06	-0.03	-3.6	-8.0	-3.6
2	0.78	0.79	0.77	0.70	0.01	-0.01	-0.08	1.5	-1.0	-9.9
3	0.29	0.27	0.27	0.33	-0.02	-0.01	0.05	-7.2	-4.7	15.8
4	2.44	2.53	2.32	1.85	0.09	-0.12	-0.59	3.7	-4.9	-24.1
5	3.74	3.61	3.50	2.72	-0.13	-0.24	-1.01	-3.4	-6.3	-27.2
6	0.76	0.75	0.76	1.09	-0.02	0.00	0.32	-2.0	0.1	42.3
7	1.60	1.55	1.55	1.75	-0.05	-0.04	0.16	-2.8	-2.5	9.9
8	0.17	0.18	0.16	0.20	0.00	-0.01	0.03	1.7	-6.4	17.0
9	0.36	0.32	0.32	0.43	-0.03	-0.03	0.07	-8.6	-9.7	20.4
10	0.55	0.51	0.52	0.56	-0.04	-0.03	0.01	-7.8	-5.4	1.3
11	3.45	3.75	3.70	3.15	0.30	0.25	-0.29	8.8	7.3	-8.5
12	2.70	2.72	2.25	2.21	0.02	-0.44	-0.49	0.9	-16.5	-18.0
13	1.40	1.21	1.18	1.30	-0.18	-0.22	-0.10	-13.2	-15.4	-7.0
14	4.84	4.48	4.62	3.69	-0.37	-0.22	-1.15	-7.5	-4.5	-23.7
15	1.42	1.36	1.45	1.41	-0.06	0.03	-0.01	-4.1	2.4	-0.7
16	3.26	3.51	3.37	2.81	0.25	0.10	-0.46	7.5	3.2	-14.0
17	2.39	2.40	2.29	1.91	0.00	-0.10	-0.49	0.1	-4.1	-20.4
18	0.51	0.54	0.50	0.52	0.02	-0.01	0.01	4.9	-2.8	1.3
19	1.13	1.23	1.16	1.05	0.10	0.03	-0.08	8.5	2.3	-7.3
20	2.51	2.69	2.62	2.21	0.17	0.10	-0.30	6.9	4.1	-12.0
Mean	1.75	1.76	1.70	1.53	0.00	-0.05	-0.22	-0.79	-3.65	-3.42
Std. Dev.	1.34	1.34	1.32	1.02	0.14	0.15	0.38	6.31	6.08	17.56

ment of volume for the reduced amount of work and man hours required, the standard deviations of the differences, both cubic meter and percent, are twice as large for the equation estimates as for the camera estimates (table 3). The percent difference numbers should be interpreted with caution since a small stem carries the same weight as a large stem. Comparison of the results from the 8 Virginia stems and the 12 North Carolina stems showed that standard deviations for the North Carolina stems were only one and a half times larger for the equation than the camera for estimates. This ratio increased to six for the Virginia stems. This indicates the effects that stand factors can have on morphological characteristics. Reliability of estimation is directly proportional to ability in matching the range (e.g., location, species, diameter classification resolution, form information, etc.) and resolution (e.g., region-level data to stand-level data, intensity of data input in model formulation) of the model used for estimation to the actual phenomena being estimated.

Chi-square Results

Error distributions failed to meet the normal distribution assumption that is inherent to the maximum anticipated error (*E*). Actual ranges found by ordering the data from smallest to largest, taking the sign into account, and examining the actual observations obtained using equation 8 are shown by the 95 percent range in table 2.

$$obs_{U\&L} = \left(\frac{n_t}{2}\right) \pm \left(\frac{(1-\alpha)n_t}{2}\right) \qquad (8)$$

where $obs_{U\&L}$ = upper and lower ordered observations representing the 1- α percent confidence level
n_t = sample size of group *t*

Comparison to the maximum anticipated error calculated disregarding the assumption shows that a reasonable approximation is still obtained using this method. The maximum anticipated errors decreased with increasing distance from the stem, asymptotically approaching ± 4 cm. The maximum anticipated errors increased from ± 2.5 to ± 7.0 cm with increasing heights from 1 to 20 m.

Sources of Errors

The mislocation of points used for diameter determination due to height and tangential differences was a cause of significant error. The diameter locations were not explicitly marked but were determined by the camera system and the conventional system independently. This source of error is magnified by stem lean—which was only accounted for in the averaging technique—and by the deliquescent branching structure of hardwood stems. The closer the camera station is to the stem, the farther the tangential points that define the edges in the image are from hypothetical caliper contact points.

Lens distortion, image plane deformation, and the orientation of the CCD array to the focal point are elements of the interior orientation of the camera that contribute to error. The greatest source of camera-related error was probably the apparent shifting of edges due to image interpolation in areas of low contrast between the stem and background reflectance.

Procedural errors of varying magnitudes and frequencies in the measurement or transfer at the ancillary data, image capture, image measurement, and calculation stages may have further contributed to error.

CONCLUSION

The conclusions of this study reveal that camera station distance should roughly be equal to the uppermost sample height to be measured using the averaging method set forth in this study. In general, shorter distances when inclination from camera station to measured point is less than 45 degrees produce the most precise results. Longer distances provide more consistent estimates with a decrease in precision at lower stem heights. The maximum anticipated error at the 95 percent confidence level for geometric mean diameters for stem heights up to 20 m on upland red oak stems using the methods set forth in this paper at a camera distance from the stem greater than 12 m is ± 4 cm. This maximum anticipated error increases with height from ± 3 to ± 7 cm at stem heights from 1 to 20 m. In this same height interval with a 12-m camera station distance, instrument precision varies from 0.8 to 1.6 cm. The expected measurement accuracy to instrument precision ratio is about 3, which is consistent with most other instruments. Volume estimates will be within 8 percent of taped measurements of individual stems two times out of three, which is an improvement over the 20 to 28 percent possible using applicable volume equations that are often not readily available. The method used in this paper provides the ability to easily formulate appropriate-scaled volume equations.

More work needs to be done to control measurement errors using the digital camera. Further experimentation using marked diameters and compensation for stem axis deviation from datum using perpendicular images should mitigate the gross errors greater than twice the image precision. The varying precision problem may be reduced by image interpolation and the image capture at longer focal lengths. The price paid for this increased precision would be a decrease in the extent of area coverage.

Comparison of this technique to results of higher precision instruments (e.g., pentaprism, rangefinder dendrometers, etc.) touting reliable diameter estimates to within ± 7 mm is not promising. However, with improvements to the automation process and ancillary data integration, this procedure has the potential to collect much more data, including spectral and spatial components that may be useful for the acquisition of other stem characteristics such as form, quality, and health information.

ACKNOWLEDGMENTS

The authors would like to thank the USDA Forest Service and Virginia Polytechnic Institute and State University for their support and cooperation in this study. The following people reviewed this manuscript: Richard G. Oderwald, Associate Professor, and Ralph L. Amateis, Senior Research Associate, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA.

LITERATURE CITED

Bell, J.F.; Groman, W.A. 1971. A field test of the accuracy of the Barr and Stroud Type FP-12 optical dendrometer. The Forestry Chronicle. 47(2): 69-74.

Clark, A., III; Schroeder, J.G. 1986. Weight, volume, and physical properties of major hardwood species in the southern Appalachian Mountains. Res. Pap. SE-253. Asheville, NC: U.S. Department of Agriculture, Forest Service. Southeast Forest Experiment Station. 63 p.

Clark, N.; Wynne, R.H.; Schmoldt, D.L.; Araman, P.A.; Winn, M. 1998. Use of a non-metric digital camera for tree stem evaluation. Technical Papers, 64th Annual meeting of the american society for photogrammetry and remote sensing. Tampa, FL. 13 p.

Freese, F. 1960. Testing accuracy. Forest Science. 6: 139-145.

Grosenbaugh, L.R. 1963. Optical dendrometers for out-of-reach diameters: a conspectus and some new theory. Forest Science. Monograph #4. Society of American Foresters. 47 p.

KODAK 1997. [WWW document]. URL http://www.kodak.com/global/en/service/faqs/faq1518.shtml#q15

Littell, R.C.; Milliken, G.A.; Stroup, W.W.; Wolfinger, R.D. 1996. SAS(R) system for mixed models. Cary, NC: SAS Institute Inc. 656 p.

Lund, H.G., ed. 1998. IUFRO guidelines for designing multipurpose resource inventories: a project of IUFRO Research Group 4.02.02 IUFRO World Series Vol. 8. 216 p.

Use of Three-Point Taper Systems in Timber Cruising

James W. Flewelling, Richard L. Ernst, and Lawrence M. Raynes

Abstract.—Tree volumes and profiles are often estimated as functions of total height and DBH. Alternative estimators include form-class methods, importance sampling, the centroid method, and multi-point profile (taper) estimation systems; all of these require some measurement or estimate of upper stem diameters. The multi-point profile system discussed here allows for upper stem measurements at any heights and constructs a smooth profile prediction that passes through all measurement points. Results from a cruise sample of trees can be summarized to allow for improved profile predictions for the non-sampled trees, which lack upper stem measurements. Decisions must be made on which measurement heights to use, which trees to sample, and how to make the upper stem measurements. The driving forces in sample efficiency are measurement error, between-tree and between-stand variation in form, and within-tree correlations at differing heights. Results from several sources are brought together to illustrate the magnitude of the variances; the focus here is on how to reduce the between-stand errors associated with taper and bark thickness. Suggestions are offered for efficient use of three-point profile systems, addressing measurement techniques, sampling methods, and summarization procedures.

A common objective of timber cruising is to estimate volume and other characteristics for particular stands. Often this is accomplished without any direct measures of tree form or volume. Volumes are estimated for sample trees based on their species, diameter at breast height outside bark (DBH), and total height (HTOT); two common estimation systems are volume prediction equations and stem profile prediction systems. The latter typically estimate diameter inside bark at any height (*h*). The usual purpose of profile prediction is as an intermediate step in predicting total volume or merchantable volume. A limitation of both taper and volume prediction systems is that for particular stands, there may be significant errors; the volume equation or taper function will be incorrect for any given stand, and the mean error may be anywhere from zero to 10 percent or more. The reasons for the errors might have to do with how the volume or taper function was fit; other, more benign possibilities include non-average tree form due to management practices, genetics, climate, or other unidentified factors. Such form differences may be major contributors to observed differences between preharvest cruises and cutout tallies.

There are several methods to overcome the above limitation. These include three-point volume equations (McTague 1992), several within-stem sampling approaches (Wiant *et al.* 1996), and multi-point profile estimation (Rustagi and Loveless 1991, Flewelling 1993a).

THREE-POINT TAPER PREDICTION SYSTEMS

The taper applications described here have all been developed as "multi-point systems" having as input: DBH, total height, and one or more upper stem diameter measurements. The user decides how many measured upper stem points are to be used in an application. In the application described here, only one upper stem measurement per sample tree is used. Some multi-point systems require the user to measure upper stem diameter at particular heights. The system developed by Flewelling (1993a) allows the user to choose the height or heights at which extra measurements are taken. That system is a generalization of a two-point prediction system. The general requirements for this formulation are:

1. A profile prediction system that predicts diameter inside bark (*d*) at any height (*h*) for a stem with measured diameter at breast height (DBH) and measured total height (HTOT).
2. An estimate of the variance (*var*) of the prediction errors (the differences between actual and estimated diameters) as a function of tree size and height (DBH, HTOT).
3. A bark thickness prediction at breast height—or a plan to measure or otherwise estimate on every tree.

Biometrics Consultant, Kent, WA, USA; Mensurationist, USDA Forest Service, Forest Management Service Center, Fort Collins, CO, USA; and Resource Information Supervisor, Rayonier Northwest Forest Resources, Hoquiam, WA, USA, respectively.

4. A formula to estimate the correlation (q) between prediction errors at any two heights on the stem.

5. A bark thickness prediction at heights other than breast height (BH).

Examples of relationships (1) to (3) are in Flewelling and Raynes (1993); (4) and (5), and the underlying theory of multi-point estimation are given by Flewelling (1993a). The essential theory is reviewed here.

Suppose that at some predetermined height on the stem (h_i), the true diameter inside bark (d_i) could be obtained; actually diameter outside bark is measured, and d_i is estimated as diameter outside bark minus an estimated double bark thickness. A standardized error (or disturbance z) can be computed as:

$$z_i = (d_i - \hat{d}_i) / \sqrt{\text{var}_i} \qquad (1)$$

where $\hat{d}_i$ is from the original stem form prediction system (a "two-point" system), d_i is the observed or measured diameter, and var_i is the estimated variance. Based on this observed error, we wish to make a revised prediction of diameter inside bark at every height on the stem. For height h_j, the appropriate estimator is based on the original estimator plus the conditional expectation of the error:

$$\hat{d}'_j = \hat{d}_j + q_{ij} \times z_i \times \sqrt{\text{var}_j} \qquad (2)$$

where q_{ij} is the estimated correlation. A sufficient rationale for the above equations is the assumption that among trees of a given size (DBH, HTOT), the diameters at any two predetermined heights have a bivariate normal distribution.

A typical cruising application of the three-point system is to measure DBH and total height on a sample of trees and to measure one upper stem diameter at a predetermined height on all or a subsample of these. The predetermined height may be a constant, or a relative height. For example, we refer to the 30 percent height as being BH + 0.3 x (HTOT - BH), where BH is breast height; this is a good height at which to measure *dob* for an improved estimate of total stem volume. Alternatively, any other relative height or a fixed height above the ground could be used. From each upper stem *dob* measurement, a *dib* estimate is inferred and converted to a z value (the "standardized" error), by means of equation 1. Thus, z is a measure of stem form, and mean z is a mean measure of form for a stand. Within a stand, the individual z values are regressed against DBH, or averaged. The average z, or the regression prediction of z, is presumed to apply to the trees that did not have an upper stem dob measurement. Diameter predictions at all other heights are from equation 2. Thus, for a typical tree lacking upper stem measurements, the inputs to the stem form prediction system are DBH, HTOT, the stand mean of z and height for which the z value is assumed to apply.

In our experience, the trend of z versus DBH is usually flat. In such cases, we recommend that the mean z be used, without regard to statistical testing for non-zero means. It is common for individual stands to have mean z values that are significantly different from zero. If this were not a common occurrence, the presumption would be that no benefit was being derived from the measurement of upper stems: either form does not vary between stands, or the sampling and measurement errors are overwhelming any stand-to-stand differences in tree form.

INGY DATA AND MODEL

The Inland Growth and Yield Cooperative (INGY) sponsored a project in 1995-1996 to collect data for and develop profile prediction equations for commercial species found in Montana, Idaho, eastern Washington and Oregon, and in the southern interior of British Columbia. The data consisted of several large historical databases, and newly collected data for 10 species. The new data were obtained by following a designed tree selection procedure in stands in all areas except British Columbia. The protocol ensured that the trees for each species would come from a large number of stands spanning site/habitat conditions, that a wide range of trees sizes (DBH, HTOT) would be felled, and that a consistent measurement protocol would be followed. Diameter inside bark (*dib*) and outside bark (*dob*) measurements were taken at regular intervals along the stem. The sample sizes for the new data are reported in table 1. The older data records involve about 13,000 trees. All data were used in the development of the stem-profile models, but the new data were accorded higher weights such that they made up about 40 percent of the total weight.

The fitted stem profile model was a variant of that reported by Flewelling and Raynes (1993); it was adopted directly from an unpublished report that Flewelling prepared for an earlier co-operative study in western Oregon and Washington. The fitting methodology was a maximum likelihood method described by Flewelling (1993b); the error distribution was assumed to be lognormal with variances dependent upon height and tree size. The thickness of the bark at heights other than breast height was modeled as a function of tree size, height, and *dob*. Statistical tests showed that tree form for some species varied by geographic region. Accordingly, models for several of the species have one or two coefficients that vary with geographic region. The models are described in an unpublished report by Flewelling and Ernst; a USDA Forest Service publication is presently in a draft stage.

Table 1.—*Numbers of sample trees by species and by numbers of sample trees per stand; INGY data set. Thus the table describes the 986 trees specially collected for the INGY project.*

Species	Numbers of sample trees per stand				
	1	2-3	4-5	≥6	All
Douglas-fir	24	59	47	34	164
Western larch	23	56	35	19	133
Grand fir/ white fir	12	50	26	29	117
Ponderosa pine	10	36	40	48	134
Lodgepole pine	14	55	33	34	136
Western red cedar	7	17	17	0	41
Hemlock	7	24	17	45	93
White pine	6	13	5	0	24
Engelmann spruce	10	39	18	7	74
Subalpine fir	6	33	16	15	70
Total	119	382	254	231	986

DATA FOR VARIANCE MODEL IN VOLUME

As explained in the introduction, a major purpose in using multi-point taper systems is to reduce the errors in volume estimation that are due to between-stand variances. To study the effectiveness of the models for this purpose, we will define several volume error variables, estimate their variance (V), and partition that variance into between-stand and within-stand components. Furthermore, we propose to estimate how much of the between-stand variance can be eliminated by the use of upper stem *dob* measurements, how this is affected by measurement error and sample size, and how much further improvement could be made by measuring bark thickness at breast height. This is all done without relying on any of the statistical assumptions made during the fitting of the model.

As part of the fitting process, total inside-bark cubic volume (including top and stump) was calculated for each tree in the database. These volumes were computed as the integration of a preliminary fit for the profile equation, plus an integration of the errors in cross-sectional area. These volume calculations should be mainly free of the biases that can arise in the more common method of assuming that each log section is a particular geometric frustum. We refer to the resultant estimate of actual total tree volume as "VOLA." Predicted total tree volumes (VOLP) come from a numerical integration of the predicted profiles; interval lengths are generally 3 percent of total height; below breast height, shorter intervals are used.

The underlying stem-form predictions are always based on DBH, total height, and where appropriate, region. Additional volume predictions are made by including various combinations of input variables, which may include one upper stem dob and the measured bark thickness at breast height (DBTbh). We number the various prediction methods according to the combinations of input variables.

1. Base (DBH, total height, region)
2. Base plus dob at 10 percent relative height (dob10)
3. Base plus dob at 20 percent relative height (dob20)
4. Base plus dob at 30 percent relative height (dob30)
5. Base, plus DBTbh
6. Base plus dob at 10 percent relative height, plus DBTbh
7. Base plus dob at 20 percent relative height, plus DBTbh
8. Base plus dob at 30 percent relative height, plus DBTbh

For each of the eight estimation systems, VOLP is predicted, and an error is calculated as:

$$ERR = \ln(VOLA / VOLP)$$

where *ln* refers to the natural logarithm. In fitting volume equations, this variable is typically assumed to have a normal distribution with zero mean and constant variance. A general linear model estimates the variance components for ERR: within-stand variance (σ_{ws}^2), and the between-stand variance (σ_{bs}^2). Restricted maximum likelihood estimation is used. The data being used are the new INGY data except that trees from the first column in table 1 are omitted—the trees that lack other within-stand sample trees of the same species. Thus, a given stand is assumed to have some unknown mean error for each species; no relationship is assumed between two species in a common stand. The resultant estimates of variance for ERR are in table 2.

Table 2.—*Variance estimates for the errors in ln(volume)*

Prediction method	Between-stand	Within-stand
1 Base (DBH, Totht, region)	.00155	.00664
2 Base & dob10	.00120	.00357
3 Base & dob20	.00081	.00288
4 Base & dob30	.00081	.00234
5 Base & DBTbh	.00117	.00570
6 Base & dob10 & DBTbh	.00068	.00322
7 Base & dob20 & DBTbh	.00030	.00266
8 Base & dob30 & DBTbh	.00020	.00200

Before we discuss the interpretation of these results, one other result is needed: the relationship between an upper stem measured *dob* and predicted volume; this will allow us to address the effect of random measurement errors in *dob*. The underlying model is:

$$\ln(VOLP' / VOLP) = m \times \ln(dob' / dob)$$

where *dob* is the actual upper stem diameter, *dob'* is the corresponding measurement with introduced error, VOLP is the predicted volume calculated using *dob*, and VOLP' is the predicted volume calculated using *dob'*. The coefficient *m* is estimated as the mean, over all trees, of *ln*(VOLP'/VOLP) divided by *ln* (1.01), where VOLP is from the three-point prediction system using actual *dob*, and VOLP' is from the same prediction system, but assuming that dob is 1 percent greater than it actually is—thereby simulating a 1 percent measurement error. For relative heights 10 percent, 20 percent, and 30 percent, *m* is estimated as 1.262, 1.318, and 1.225, respectively. Simulations of other errors in *dob*, from -5 percent to +5 percent confirm that the relationship between ln(dob) and ln(VOLP) is almost linear. Although this sensitivity relationship is calculated at an aggregate level, it is assumed to be approximately correct at the individual tree level.

VARIANCE MODEL IN VOLUME

If in application every species in every stand had a sufficiently large sample of trees, the resultant between-stand errors in volume (by species) would be as indicated in table 2. Using only the base measurements, the variance in errors for *ln*(volume) would be 0.00155, corresponding to a between-stand standard deviation of about 3.9 percent. This is in addition to the normal sampling errors and reflects only the stand-to-stand uncertainty in stem form and bark thickness. In method 4, which requires measurements of dob at 30 percent relative height, the between-stand variance drops to .00081, corresponding to a standard deviation of 2.8 percent. Hence, measurements of *dob* at relative height 30 percent reduce the error variance (at the stand level) by almost half. A further reduction in variance occurs if bark thickness at breast height is also measured. The total error for a species' volume will, of course, be increased due to sampling errors in basal area and height; these sources of error are not addressed.

For finite sample sizes, the actual benefits of the additional measurements (*dob* at a relative height and/or DBTbh), will be less than that indicated by table 2. For example, if in a stand only one tree of a given species had an upper stem measurement made at a relative height of 30 percent, with the resultant *z* value applied to all trees, the between-stand error due to stem form would increase from .00155 to .00315 (the sum of the two variance components associated with method 4). The general formula for the resultant between-stand variance, including intrinsic (I) and sampling effects (S) is:

$$V(I+S)_{bs} = \sigma^2_{bs} + \sigma^2_{ws} / \sqrt{N}$$

where N is the number of trees with sampled upper stem *dob*'s. The above formula is exactly correct for a simplified situation. Consider that in summarizing a cruise, the mean of ln(VOLP3 / VOLP2) is to be calculated, where VOLP2 and VOLP3 are volume predictions based on the two-point and three-point sytems, respectively, and that the resultant mean value is to be used in adjusting the usual two-point estimate of volume for the stand; the final volume prediction for the stand will be the base volume estimate times the exponential of the mean ln(VOLP3 / VOLP2). The reader may recognize that these calculation are closely related to typical "vbar" calculations. But the point we wish to make is that the resultant calculation of stand volume (adjusted for the upper stem measurements) will be almost the same as though a mean *z* had been obtained for the upper stem measured trees and applied to all trees. This is easy to verify with cruise results. Assuming this assertion is correct, then the sampling variance for mean ln(VOLP3 / VOLP2) declines with the square root of N, and the variance formula must be correct. The reason we choose to summarize by mean z rather than by mean ln(VOLP3 / VOLP2) is that in doing so we obtain more than just volume; we get fully compatible profiles for all trees and the ability to generate Scribner volumes or log assortment tables.

Measurement error in *dob* will cause a further increase in between-stand variance in the error for *ln*(VOL). That variance may be estimated by using the relationship between *dob* and predicted volume. The variance in ln(VOL) associated with measurement error in *dob* is:

$$\sigma^2_{me} = m^2 \times \sigma^2_{dob}$$

where *m* is coefficient reported in the previous section, and σ_{dob}^2 is the measurement variance for ln(*dob*) at the recorded height. For example, at a 10 percent relative height, with a 1 percent standard deviation in dob due to measurement error:

$$\sigma^2_{me} = 1.262^2 \times 0.0001 = 0.00016$$

Recall that the within-stand variance in ln(VOL) error (for a prediction using *dob* at 10 percent) is 0.00357; hence, the variance being added by a random 1 percent measurement error is relatively unimportant. The general formula for between-stand variation in volume error due to intrinsic differences in form (I), sampling for upper stem *dob*'s (S) and measurement error (ME) on the *dob*'s, is:

$$V(I+S+ME)_{bs} = \sigma^2_{bs} + \frac{\sigma^2_{ws} + m^2 \times \sigma^2_{dob}}{\sqrt{N}}$$

Predictions from the above equation are in table 3. In viewing that table, recall that a between-stand variance in error for ln(volume) of 0.00155 can be obtained without using any upper stem measurements. Thus, sampling for upper stem measurements using small sample sizes or large measurement errors will increase the variability of the error in estimating volume for a stand.

The majority of the INGY sample trees are of species that are not the most prevalent in their respective stands. Within each stand, the sample trees will tend to have a highly variable selection of tree sizes. These two facts would lead us to the suggestion that the σ_{ws}^2 values in table 2 are greater than would typically be seen in the primary species for single-age stands. We have a database that allows us to estimate σ_{ws}^2 within a 40-year-old Douglas-fir stand in the Willamette National Forest, about 50 miles west of Eugene, OR. In that stand, 44 representative trees were felled; inside bark and outside bark diameter measurements were made along the stem. We determined total volume for each tree, calculated predicted volumes based on DBH, HTOT, and dob at 33 feet. The percentage errors in volume were summarized: mean 0.5, standard deviation 3.4. This has an approximate correspondence to a σ_{ws}^2 value of 0.00116. This is about half of the estimated within-stand variance for method 4, as reported in table 2. Hence, it is possible that many important cruising situations will have within-stand variances much lower than indicated by the table.

Table 3.—*Between-stand variance in error for ln(volume), considering form differences, sampling error for upper stem dob and measurement error of upper stem dob. The measurement error refers to the standard deviation of the error in measuring ln(dob). N is the number of sample trees for which an upper stem dob is obtained.*

Rel. Ht (%)	Meas Err	N=8	N=16	N=32	N=64	N=128	N=infinity
10	0	.00246	.00209	.00183	.00165	.00152	.00120
	.01	.00252	.00213	.00186	.00167	.00153	.00120
	.03	.00297	.00245	.00208	.00183	.00164	.00120
	.05	.00387	.00309	.00253	.00214	.00187	.00120
20	0	.00183	.00153	.00132	.00117	.00106	.00081
	.01	.00189	.00157	.00135	.00119	.00108	.00081
	.03	.00238	.00192	.00160	.00137	.00120	.00081
	.05	.00336	.00262	.00209	.00171	.00145	.00081
30	0	.00164	.00140	.00122	.00110	.00102	.00081
	.01	.00169	.00143	.00125	.00112	.00103	.00081
	.03	.00211	.00173	.00146	.00127	.00114	.00081
	.05	.00296	.00233	.00189	.00157	.00135	.00081

DISCUSSION

The analysis of the variance components presented above can be coupled with expectations of precision and accuracy for various instruments to devise cruising plans that will lead to improved estimates of stand volume. In applying any taper system, validation of the system is to be recommended. However, the three-point system can be applied to populations different from those used in fitting without nearly as much risk as for a two-point system. With a three-point system, the biggest risk is that the upper stem dob's will be measured in a biased fashion.

References to measurement error for upper stem dob's are Schmid-Hass and Winzeler (1981), Winzeler (1986), Skovsgaard *et al.* (1998), and other papers in the present symposium. Precision depends on diameter and measurement height. For diameters of 30 cm at a height of 7 m. Schmid-Haas and Winzeler report standard deviations ranging from 1.3 percent for the Finnish caliper to 3.8 percent for the Relaskop. The cited publications all mention bias as a very serious problem; it can be due to individual operator error, instrument miscalibration, or systematic errors in the use of the instruments. In validation of field techniques, the use a paint-ball gun to mark a target height is recommended. This allows the two potential sources of error—due to height measurement and *dob* measurement—to be separately tracked. The measurement variance referred to in the previous section, σ_{dob}^2 , is, of course, based on a comparison of the recorded diameter and the actual diameter at the recorded height (which is not necessarily at the paint mark).

Field techniques must be used correctly for any cruising or inventory situation. A good stem form model can help detect measurement biases. Using a profile model similar to the INGY model, we helped identify two sources of bias in USDA Forest Service field measurement procedures. Measuring upper stem diameters on standing trees is difficult, particularly at greater heights. In Forest Service tests, the Criterion laser was used to determine upper stem diameters; however, we used the instrument inappropriately. We had used the laser to calculate the horizontal distance to the face of the tree at DBH rather than to the vertical projection of the face of the tree at the upper bole measurement point. Because the calculations built into the laser assumed a horizontal distance to the face of the tree at the upper bole measurement point, the resulting answer had a consistent bias. The calculations done by the instrument resulted in an understatement of the upper stem diameter; adjusting the profile model for this understated upper bole diameter results in an apparent faster taper, resulting in an underprediction of volume.

Another problem exists with mixing and matching diameter tape and caliper measurements; for example, using a d-tape to measure DBH and an optical instrument (i.e., Caliper) to measure upper bole diameters. To determine the taper rate, both diameters should be taken with calipers or both should be taken with the d-tape; since a taped measurement of the upper bole is not practical, an additional caliper measurement should be used for taper rate calculation. We have data from a previous study where we took standing tree diameter measurements with a tape, mechanical calipers, Barr & Stroud dendrometer, and Criterion Laser; the mechanical caliper measurements were taken up the bole by climbing the tree. An analysis of the 300+ DBH measurements indicated that on the average, the taped diameter at breast height was slightly larger than the average caliper measurement. Again, using the taped DBH with a caliper upper bole measurement resulted in an overstatement of taper rate.

At the time of model development, and again prior to model implementation, some form of validation should be done to test the ability of the model to predict accurately and precisely. Where possible, validate a model by using data collected independently of data used to build the model. An important additional part of the validation process, particularly for two-point applications, should include the monitoring and re-evaluation of these models over time. This is necessary to have a continuing level of confidence that the models are producing reliable estimates of volume across the range of size and geographical areas they are being used in. Additionally, sampling techniques can be used to estimate the bias attributable to a taper system for a particular region.

The flexibility of the multi-point taper systems described here allows them to be used in several ways. These include:

1. As a two-point model—since most models are developed from data collected over broad areas, the models should predict profiles (and thus volumes) "on the average" very well throughout the area.

2. As a three-point (or multi-point) model—more accurate but involves additional measurements, thus more costly. One or more upper stem dob's are measured at predetermined heights on each tree being cruised; these measurements provide additional information for the model to predict profile, allowing individual tree profile differences to be recognized.

3. As a two-point model with a three-point subsample—a compromise between the first two options. Since it requires additional effort and cost to collect upper stem measurements, you may want to minimize the number of trees where they are taken; sampling, for example in the pre-cruise, could be used to calculate an average z value, or alternatively a three-point to two-point volume ratio, with the selected summary

applied to all trees in the cruise. It could be hypothesized that taper is a function of a tree's competative position in the stand, and therefore, the *z* score could be regressed on DBH. However, based on 2 years' experience with several forest types, it seems that a simple average for the stand is adequate.

4. With an assumed taper or *z* score—past experience may indicate that a particular stand type or subregion has a consistent taper, and an assumed *z* score could therefore be used.

The profile predictions are based on a system of equations; part of that system is a prediction of bark thickness at breast height. That prediction is, of course, reflective of the bark thicknesses observed in the original data set. In practice, we have found that there is substantial variability in double bark thickness at breast height, both between trees within stands, and between stands. Since bark thickness at breast height is fairly easy to measure and has the potential for large improvements in volume accuracy, it should be considered as a measurement variable. However, it is critical to verify that such measurements can be made without bias.

SUMMARY

The application of multi-point taper systems to cruising has been reviewed. The variance analyses suggest that fairly large numbers of trees must be measured for upper stem *dob* in order to reduce the between-stand variance in estimated volume. The requirement for large samples is driven by the high within-stand variance in stem form. Because of the way the data were obtained, that variance may be higher than will typically be found in a relatively homogeneous stand, with one or two major species. The supposition that smaller samples of upper stem dob's are adequate is supported by the low within-stand variance found in one Douglas-fir stand, and by the observation that significant mean *z* values can be found often with cruised samples of 30 to 40 trees. In measuring the upper stem *dob*'s, bias is to be carefully guarded against by validating measurement techniques and calibrating instruments. In addition to using upper stem dob's, there is a potential for using measured bark thickness at breast height.

The techniques described here work well with what we believe to be good taper systems. However, if the underlying two-point taper system has biases, the multi-point system has the ability to greatly reduce those biases. In some of the species we have worked with, there are hints of some small biases—namely a fairly consistent trend of negative mean *z* values for stands in some areas. If three-point taper cruising is used, the effect of any biases is greatly reduced. However, if the three-point cruising introduces measurement bias, it can change an unbiased prediction system into a biased prediction system.

ACKNOWLEDGMENTS

The data and original funding were provided by the participants in the Inland Growth and Yield Cooperative (INGY) taper study. The cited west coast Douglas-fir data were provided by Criss Roemer of the USDA Forest Service, Portland, OR, USA. Reviewers were Steen Magnussen, Pacific Forestry Center, Victoria, and Fred Martin, Washington Department of Natural Resources, Olympia, WA, USA.

LITERATURE CITED

Flewelling, J.W. 1993a. Variable-shape stem-profile predictions for western hemlock. Part II: Predictions from DBH, total height and upper stem measurements. Canadian Journal of Forest Research. 23: 537-544.

Flewelling, J.W. 1993b. Stem form and volume estimation based upon measured height, DBH, and one or more upper stem measurements: a stochastic process approach. In: Wood, G.B.; Wiant, H.V., Jr., eds. Modern methods of estimating tree and log volume, IUFRO conference proceedings; 1993 June 14-16. Morgantown, WV: West Virginia University Publication Service: 58-67.

Flewelling, J.W.; Raynes, L.M. 1993. Variable-shape stem-profile predictions for western hemlock. Part I: Predictions from DBH and total height. Canadian Journal of Forest Research. 23: 520-536.

McTague, J.P. 1992. Enhanced estimates of total volume with any single upper-stem measurement. Forest Ecology and Management. 48: 55-67.

Rustagi, K.P.; Loveless, D.R. 1991. Compatible variable-form volume and stem-profile equations for Douglas-fir. Canadian Journal of Forest Research. 21: 143-151.

Schmid-Haas, P.; Winzeler, K. 1981. Efficient determination of volume and volume growth. In: Nishizawa, M., ed. Proceedings of the 17th IUFRO World Congress; 1981 September 6-17; Kyoto, Japan. Subj groups 4.0, 4.02, 4.04, and 6.02. Nigata, Japan: Japan Association for Forest Statistics, Nigata University: 231-257.

Skovsgaard, J.P.; Johannsen, V.K.; Vanclay, J.K. 1998. Accuracy and precision of two laser dendrometers. Forestry 71: 131-139.

Wiant, H.V., Jr.; Wood, G.B.; Williams, M. 1996. Comparison of three modern methods for estimating volume of sample trees using one or two diameter measurements. Forest Ecology and Management. 83: 13-16.

Winzeler, K. 1986. Volumenbestimmung durch Messungen am stehenden Baum [Volume determination through measurements on standing trees]. Mitteilungen 16, Swiss Federal Institute of Forestry research.

APPENDIX A.— Determining Diameter of a Standing Tree Anywhere Along the Bole Using a Relaskop

The Spiegal-Relaskop, and in fact any angle gauge, can be used to measure tree diameters at any height along the bole that is clearly visible. Measurement techniques that avoid interpolation on the scale may be the most precise. For example, usage of an American Scale Relaskop, using a 75.6 Basal Area Factor (BAF), located approximately in the middle of the fifth white bar to the right of "0" on the scale, is described. Attach a measuring tape to the center of the tree, and while viewing through the Relaskop, back away until the left side of the tree touches the "0" scale, and the right side of the tree touches the middle of the fifth white bar, or the equivalent of a borderline tree. At this point, the distance away from the tree in feet equals the diameter of the tree in inches. The Relaskop adjusts for slope, so the diameter can be measured at any height along the bole.

The following formulas show the calculation of the diameter using any BAF:

$$dia = \frac{dist}{PRF}$$

where :

dia is the diameter of the tree in inches

$dist$ is the distance to the tree in feet

$PRF = \frac{8.696}{\sqrt{BAF}}$ is the plot radius factor

When using the Relaskop, a convenient relationship of 1 inch diameter for each foot of distance from the tree results with a 75.6 BAF (midpoint of the fifth white bar); the calculation results in a PRF=1. The formulas allow you to use any BAF, although it is not a direct one-to-one relationship as with the 75.6 BAF. Also note that when using a prism, to adjust for slope, tilt the plane of the prism so that it is perpendicular to the line of site to the point of measurement on the bole.

A Field Test of Cut-Off Importance Sampling for Bole Volume

Jeffrey H. Gove, Harry T. Valentine, and Michael J. Holmes

Abstract.—Cut-off importance sampling has recently been introduced as a technique for estimating bole volume to some point below the tree tip, termed the cut-off point. A field test of this technique was conducted on a small population of eastern white pine trees using dendrometry as the standard for volume estimation. Results showed that the differences in volume estimates between the techniques were generally within acceptable limits.

Importance sampling, since its first appearance in the forestry literature over a decade ago, has been used to estimate numerous dimensions of trees. Originally introduced in conjunction with randomized branch sampling by Valentine *et al.* (1984) to estimate total, aboveground, woody volume and dry matter, it has proven to be an adaptable technique. For example, importance sampling provides unbiased estimates of bole volumes in conjunction with tree-selection schemes like 3-P (Gregoire *et al.* 1986). It also can be used to estimate log volume (Furnival *et al.* 1986) and bole increment (Gregoire *et al.* 1987).

In the above contexts, importance sampling is generally applied to the entire unit to be sampled, whether a log or the entire bole. Cut-off importance sampling (CIS) is a variant of the usual importance sampling where an intermediate point is used as a cut-off for the sampling process. For example, in the estimation of tree bole volume, one might use merchantable height or height to the base of the live crown as logical cut-off points, depending upon the application. One or more heights along the tree bole from base (or stump) to the cut-off point are chosen by a probability mechanism for measurement of diameter. The measurement converts to an essentially unbiased estimate of bole volume for that bole section in which sampling occurs. Estimates for total bole volume are also possible. Since its introduction by Robinson *et al.* (1997), however, there has been little else published on cut-off importance sampling for bole volume. These authors presented a field test in which CIS performed well in the estimation of bole volume as compared with importance sampling. In this paper, we present a field test of CIS in the northeastern U.S. CIS is compared with detailed dendrometry of the population of trees of interest.

METHODS

A population of 74 eastern white pine (*Pinus strobus)* trees in a well-managed, even-aged, research stand on University of New Hampshire woodlands, Durham, NH, was used in this study. All of the trees in the stand are numbered, and the stand has been subjected to various intensive silvicultural methods in the past to try to promote advanced regeneration, including several controlled burns. Average diameter at breast height (dbh) for the stand was 17.8 in., average total height was 83.8 ft, and the average live crown ratio was found to be approximately 46 percent. Each tree in the stand was measured using a Barr and Stroud (B&S) FP-12 optical dendrometer and subsequently resampled using CIS. Measurements required for dendrometry began at the base of the tree—both stump diameter at 1.5 ft and dbh were measured with diameter tapes. From dbh, the first actual B&S measurement was always taken at a height of 4 ft above dbh, located with a measuring pole. In general, other B&S measurements were taken at points that reflected the taper of the tree rather than at set regular intervals. The only other exception to this rule was that a B&S measurement was always taken at the base of the live crown to facilitate comparison with the CIS estimates. Sixty-eight trees were actually used after excluding those trees with forks, broken tops, or other abnormalities that did not lend themselve to the techniques described below.

The dendrometry measurements were recorded in a format compatible with STX (Grosenbaugh 1974, Rennie 1977, Space 1974). A separate FORTRAN-90 program that also read STX input file formats was written to compute cubic foot volumes from the dendrometry cross-sectional areas and heights via three different spline algorithms: natural cubic splines (Press *et al.* 1986), hermite polynomials, and the method of Akima (de Boor 1974, IMSL 1994). This latter program also computed cubic foot volumes by conic sections as in STX. The Akima method was judged to be the best of the three splining algorithms used and was therefore retained in this analysis along with the conic section method. These methods allowed for interpolation of cross-sectional areas

---

Gove and Valentine are Research Foresters, USDA Forest Service, Northeastern Research Station, P.O. Box 640, Durham, NH 03824, USA; and Holmes is Forest Biometrician, Plum Creek Timber Company, P.O. Box 1990,Columbia Falls, MT 59912, USA.

(and hence diameters) at any height from the fitted splines, or by linear interpolation between the measured diameters. Calculation of volume was also possible to any height by direct integration of the Akima spline functions or again, by linear interpolation from the measured conic section volume. Specifically, diameter and volume were desired to the base of the live crown to compare with those taken in the CIS procedure described subsequently. All volumes and diameters in this analysis included bark.

In all comparisons of volume and height measurements between the two techniques, the dendrometry measurements are taken as the "true" values for each tree with full regard to the measurement errors and biases associated with this technique. Accuracy of the CIS estimates can therefore be determined using a chi-square approach first put forth by Freese (1960), who suggested several variations on this statistic. The version used here is based on the error sums of squares from a simple linear regression of the CIS estimates on the dendrometry estimates. In this statistic, the standard method (dendrometry) is the independent variable in the regression. This may seem backwards because one might naturally want to think in terms of using the CIS estimates to predict the standard. However, a little reflection on OLS theory reminds us that the independent variable is assumed fixed (constant and measured without error) while the dependent variable is the random variable; therefore, the standard method is taken as the independent variable in this regression. According to Freese (1960), this is an approximate test that corrects for linearly increasing or decreasing bias with respect to the dendrometry data; such linear trends were common in these data (fig. 1). The form of the test is given as

$$\chi^2_{(n-2)df} = \frac{sse}{\sigma^2} \qquad (1)$$

where sse is the regression error sum of squares and σ^2 is the hypothesized variance; it is defined as

$$\sigma^2 = \frac{E^2}{z^2}$$

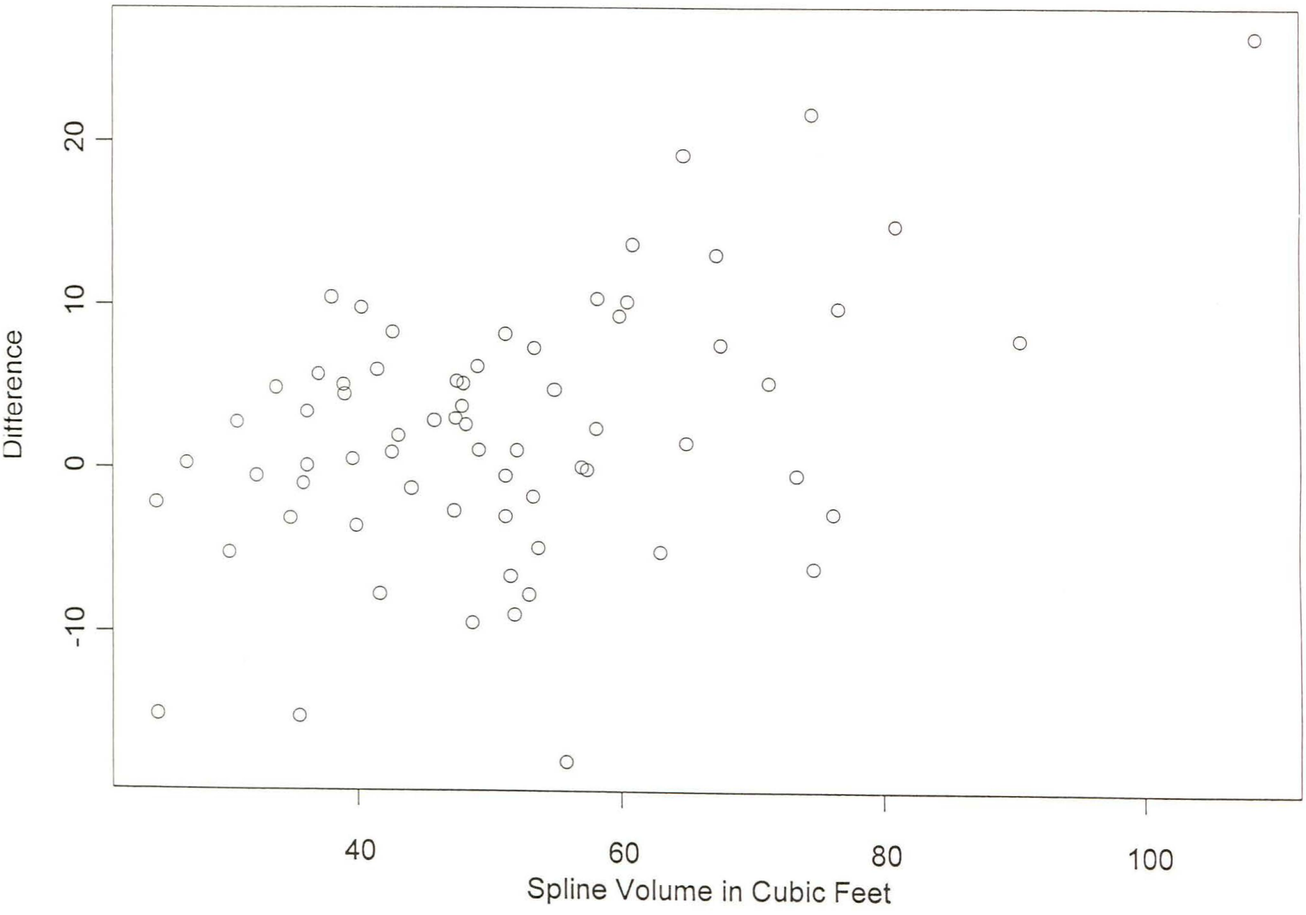


Figure 1.—*Difference in volume to the base of the live crown:* $V_S(H_L,H_C)-\tilde{V}(H_L,H_C)$.

Here, E is the allowable error in the same units as the variable to be tested and z is the standard normal deviate at the required significance level. The significance level was set to 0.05 for all tests. In each accuracy test done, the allowable error was specified to be 5 percent of the mean for the dendrometry-base variable of interest; these values are shown in table 1. Using a simple re-arrangement of (1), it is possible to determine what the "target" allowable error ($\tilde{E}$) would have to be in order for the desired accuracy to be met in each test (Bell and Groman 1971); these are also presented in table 1.

Cut-off importance sampling has been described in detail by Robinson *et al.* (1997). In this study, the portions of the tree bole of interest lay between a 1.5-ft stump height (H_L), height to the base of the live crown (H_C), and total height (H_U). CIS was conducted on each tree between H_L and H_C. A Finnish caliper (Schmid and Werner 1970) was used to measure the diameter at the randomly chosen cut-off height within this section. Heights of CIS sample points were measured with a height pole; a clinometer was used to measure total height and height to the base of the live crown. Volumes of interest include volume from stump to live crown base ($V(H_L,H_C)$), and total volume from stump to tip ($V(H_L,H_U)$). CIS theory provides estimators for both of these volumes; they are given in Robinson *et al.* (1997). Denote the CIS estimator of $V(H_L,H_C)$, as $\hat{V}(H_L,H_C)$, and the CIS ratio estimator of total volume as $\tilde{V}(H_L,H_U)$. The proxy taper function used here is the same as that used by Robinson *et al.* (1997) with $C = 4$; viz.,

$$A_p(h)=A(H_B)\left[\frac{H_U-h}{H_U-H_B}\right]^{4/c}$$

Here, A(•) denotes the bole cross-sectional area, H_B is breast height, h is any height in the range $H_L \le h \le H_U$. Furthermore, let the volumes from dendrometry computed via the spline and conic sections be denoted $V_S(H_L,\cdots)$ and $V_C(H_L,\cdots)$, respectively to either the base of the live crown or the tree tip.

RESULTS

Height Comparisons

The dendrometry and CIS were conducted independently by the same crews, approximately 2 weeks apart. No attempt was made to mark the base of the live crown on each stem. Therefore, this point differed somewhat between the two samples. As such, it is expedient to first see if these points coincide for the two different inventories on average. Because this point was a judgment call in both instances, neither can be considered the "true" value and, therefore, Freese's technique is inappropriate. A paired *t*-test was used instead to test the null hypothesis that the mean difference between the two points was equal to zero. This could not be rejected at the $\alpha = 0.05$ level; thus, the points can be considered the same between the two methods, even though there were rather large differences on some trees (table 1). This assumption facilitated the calculation of volumes to the base of the live crown (BLC) between the two methods because no interpolation was required initially for the computation of either spline or conic section volumes.

Total height comparisons were between the clinometer measurement from the CIS sample and the dendrometry measurement. Remarkably, there was little overall bias in the clinometer estimate of total tree height (table 1). However, the MSE shows that there was a fairly large

Table 1.—*Comparison of dendrometry and CIS estimates for tree heights and volumes for N=68 eastern white pines*

	Mean B&S	Mean CIS	E	$\tilde{E}$	Percent $\tilde{E}$	Average Difference	MSE
Height to BLC (ft)	39.0	40.5	—	—	—	1.5	48.5
Total Height (ft)	83.8	86.6	4.2	9.0	11	2.8	41.3
Volume to BLC (ft^3)							
Spline	51.3	48.9	2.6	12.3	24	-2.3	68.7
Conic Section	51.2	48.9	2.6	12.1	24	-2.3	65.3
Total Volume (ft^3)							
Spline	69.4	72.0	3.5	15.6	22	2.6	86.7
Conic Section	68.6	72.0	3.4	15.2	22	3.4	87.8

amount of variability associated with these readings. Indeed, the accuracy test inference is that the two methods are different, unless one is willing to accept an 11 percent, or 9 foot, allowable error.

Volume Comparisons

Inasmuch as the heights to the BLC between the two measurement periods were not found to be different on average, the two (possibly) different heights were used for the calculation of volume to the BLC via CIS and dendrometry (table 1). The first thing to notice is that both the spline and conic section volumes to BLC were very close; hence, these two methods could be used interchangeably to compare against the calculated CIS volumes. CIS estimates are slightly less than the spline and conic section volumes by approximately 4 percent on average. Likewise, the total volume estimate by CIS to BLC for all 68 trees is 4.6 percent less that the total spline and conic section volume. However, regarding the last two columns of table 1, notice that the standard deviation of these differences is almost four times the mean. This large degree of variability is found to influence the chi-square test so that one would have to accept a 24 percent allowable error before the two methods could be considered comparable.

The results on total bole volume were much the same as for volume to the base of the live crown (table 1). In this case, the difference was slightly greater and in the opposite direction from the results on volume to BLC. But again, the large variance dominates the mean squared error with a standard deviation of 9 cubic feet on the difference between $V_S(H_L,H_U)$ and $\widetilde{V}(H_L,H_U)$. As a consequence, one would have to accept an allowable error of approximately 15.5 cubic feet, or 22 percent, for the CIS estimate of total bole volume to be considered as accurate as the dendrometry. In addition, the sum of the volumes for all 68 trees produced a positive difference of approximately 4 percent. For total volume, the spline and conic section volumes were not quite as close as for volume to BLC; however, a simple linear regression of $V_C(H_L,H_U)$ on $V_S(H_L,H_U)$ still had $R^2 = 0.99$.

DISCUSSION

Because the cut-off point at the base of the live crown was estimated independently for CIS and dendrometry, the spline and conic section volumes were recalculated to the estimated height to BLC,H_C, from CIS. Even though the paired *t*-test led to no difference in the respective heights to BLC on average, using one height for both methods should make for more consistency in the results. Indeed, the averages for spline and conic sections in this case were 52.2 and 52.1 ft^3, respectively; this led to average differences of -3.3 and -3.2 ft^3. Note that the average difference has actually increased by using the common BLC cut-off height for volume comparison. However, the MSE for CIS comparisons with spline and conic section volumes were 44.9 and 42.9, respectively. This decrease in MSE is attributable to a substantial decrease in variance as would be expected. Instead of being approximately four times the average difference, the standard deviation of the differences has decreased to only 1.5 times the average difference. The chi-square test reflected the increase in precision even with the larger difference. The results showed that instead of requiring an allowable error of 24 percent using the independent heights to BLC, this has now dropped to an allowable error of 18 percent. As Freese (1960) notes,

> Inaccuracy may be due to lack of precision, to bias, or to a combination of these. The chi-square technique will reject regardless of the source of inaccuracy. However, the test can be modified to evaluate accuracy after elimination of bias.

The results of the bias-adjusted approximate test used here shows that even though the difference increased using the same height to BLC, the decrease in the variance component led to better accuracy on average.

In cut-off importance sampling, heights at which sampling takes place are selected in the lower portion of the bole between H_L and H_C, whereas in traditional importance sampling as described by Gregoire *et al.* (1986), the height to be sampled can fall anywhere within the bole. In this study, it was found that the clinometer estimates of total height had a significant bias compared to the B&S heights and that they varied greatly from tree to tree. If a clinometer were used to determine total height in traditional importance sampling, this height-measurement bias would also affect the final estimate of volume since it enters into the estimator for total bole volume through the proxy volume and associated probability density function. One important strength that CIS has over traditional IS is the fact that the total height does not enter into the calculation for bole volume below the cut-off point. If this point is chosen wisely, such as the base of the live crown, then one should be able to measure any height within the region $[H_L,H_C]$ with good accuracy as in this study. If total bole volume is desired, however, then the estimate of total height does again enter into the calculation through the ratio estimator, and one should strive for accuracy in the total height estimates.

ACKNOWLEDGMENTS

The authors would like to thank Mr. William B. Leak and Dr. Lianjun Zhang for their review of this manuscript.

LITERATURE CITED

Bell, J.F.; Groman, W.A. 1971. A field test of the accuracy of the Barr and Stroud type FP-12 optical dendrometer. The Forestry Chronicle. 47(2): 1-6.

de Boor, C. 1978. A practical guide to splines. NY: Springer-Verlag. 392 p.

Freese, F. 1960. Testing accuracy. Forest Science. 6(2): 139-145.

Funrival, G.M.; Valentine, H.T.; Gregoire, T.G. 1986. Estimation of log volume by importance sampling. Forest Science. 32(4): 1073-1078.

Gregoire, T.G.; Valentine, H.T.; Furnival, G.M. 1986. Estimation of bole volume by importance sampling. Canadian Journal of Forest Research. 16: 554-557.

Gregoire, T.G.; Valentine, H.T.; Furnival, G.M. 1987. Sampling methods for estimating stem volume and volume increment. Forest Ecology and Management. 21: 311-323.

Grosenbaugh, L.R. 1974. STX 3-3-73: Tree content and value estimation using various sample designs, dendrometry methods, and V-S-L conversion coefficients. Res. Pap. SE-117. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 112 p.

IMSL. 1994. Math library. Houston, TX: Visual Numerics, Inc. 1,141 p.

Press, W.H.; Flannery, B.P.; Teukolsky, S.A.; Vetterling, W.T. 1986. Numerical recipes: the art of scientific computing. NY: Cambridge University Press. 818 p.

Rennie, J.C. 1977. A computer system for processing timber inventory data. Unpublished report presented at Sampling techniques and timber inventory systems workshop; 1977 August 29-September 2; Athens GA.

Robinson, A.P.; Gregoire, T.G.; Valentine, H.T. 1997. Cut-off importance sampling of bole volume. Silva Fennica. 31(2): 153-160.

Schmid, P.; Werner, J. 1970. Swiss continuous forest inventory. Swiss Forest Research Birmensdorf/ Zurich: Institute.

Space, J.C. 1974. 3-P forest inventory: design procedures, data processing. U.S. Department of Agriculture, Forest Service, State & Private Forestry-Southeastern Area. 58 p.

Valentine, H.T.; Tritton, L.M.; Furnival, G.M. 1984. Subsampling trees for biomass, volume or mineral content. Forest Science. 30(3): 673-681.

Reliability Assessment of Selected Indicators of Tree Health

Pawel M. Lech

Abstract.—The measurements of electrical resistance of near-cambium tissues, selected biometric features of needles and shoots, and the annual radial increment as well as visual estimates of crown defoliation were performed on about 100 Norway spruce trees in three 60- to 70-year-old stands located in the Western Sudety Mountains. The defoliation, electrical resistance, and length of an individual shoot were classified as least reliable and of lowest diagnostic usability out of 17 parameters tested as estimates of tree health. In contrast, coefficients such as dry mass of one needle and dry mass of needles next to last set (per one shoot, per 1 cm of shoot) were evaluated as the most credible indicators of tree health. The normative scale of health, as expressed by the values of selected reliable coefficients, was then determined to allow an objective assessment of Norway spruce tree health.

Forest monitoring is one of the essential sources of information about forest health. It has been providing data in a spatially, chronologically, and, what is most important, methodologically uniform order on the European level since 1980's. However, the results obtained within its frame don't allow a clear interpretation. This is particularly obvious in such cases as the crown status—environmental condition relationship and causes of observed damages or disease symptoms. Thus, it seems plausible to analyze the reliability of the methods and criteria currently used in the monitoring of forest health and to consider their modification or replacement.

In the European, transnational survey, visually estimated defoliation of tree crown and discoloration of leaves are practically the only parameters on which the estimation of forest health is based. Each of 20 trees located on the permanent sample plot is assessed in comparison to a reference tree of full foliage and no symptoms of discoloration. The photographs of a healthy tree suitable for the region under investigation may serve as an aid, especially when no reference tree can be found in the vicinity of the plot. The results of defoliation assessment are recorded in 5 percent steps. It is widely accepted to treat defoliation larger than 25 percent as damage and evidence of the decreased health status of a tree. Such a quantity of defoliation corresponds to defoliation class 2 and 3 in the UN/ECE and EU classifications.

Numerous researchers have confirmed the usability of defoliation as an indicator of tree health. A positive relationship has been found between defoliation and loss of tree volume increment (Waring 1983, Soderberg 1991, Trampler *et al.* 1992, Wilmot *et al.* 1995), but a negative dependence has been found between defoliation and leaf chlorophyll content or nutrient status (Stachurski *et al.* 1994). These relationships result from the inhibition of the intensity of basic physiological processes, such as photosynthesis, uptake and transport, and, in effect, a decrease in sugars and other energy substances in leaves. This leads to a reduction in growth rate and is a predisposing factor inhibiting natural resistance of an organism to diseases.

Despite the results of these investigations, there is still a controversy about using defoliation as one of or sometimes the only indicator of forest health, which has commonly happened in the European monitoring programs. Two basic critical approaches can be distinguished. The first one undermines the commonly accepted rule that "the greater degree of crown defoliation of individual trees, the worse health condition of or the greater damage to the forest." The second approach focuses on the accuracy of the method of defoliation assessment and, as a consequence, on the reliability of forest health estimates.

Based on the analysis of the available historical data, Kandler (1992) and Schweigruber (1989) stated that the degree of defoliation is not an adequate indicator of the tree health. They pointed out that the trees, which presently display a good health condition and vitality would, from the early-century crown photographs, have been classified as severely damaged. Mayer *et al.* (1980) and Mueller-Dombois (1987) analyzed a stand-level breakdown and recovery on a spatially rotating basis. They reported that the forest fractions, where a stand is in the phase of breakdown attributed to processes of generation or species succession, are the natural components of the virgin forest spatial structure. Unlike the managed forests, in which such a phenomenon is observed over

---

Research Assistant, Forest Research Institute, Department of Forest Phytopathology, ul. Bitwy Warszawskiej 1920r. 3, 00-793 Warszawa, Poland, e-mail: p.lech@ibles.waw.pl

large areas, these fractions are small and scattered within the forest complex and they form a spatial mosaic. Recovery (reintegration) of a forest ecosystem follows rapidly and creates an impression of internal harmony (stability) in an ecosystem and of the smoothness of changes. It also means that the dieback of individual trees or species on the ecosystem level is not the symptom of a total destruction but rather the manifestation of the succession dynamics and the adaptive ability of the forest (Mueller-Dombois *et al.* 1983).

The most controversial issue, however, is the estimation method of the degree of defoliation, which according to the ICP-Forest methodology is subjective and not repeatable. It has been stated that defoliation determined in this way does not reflect the true crown condition of a tree as described by biometric parameters of the assimilating apparatus (Sierota 1990, 1991) or by the electric resistance indices of near-cambium tissues (Rykowski 1984). Researchers have also pointed out the low precision of defoliation estimates. The reason for that has been sought in variations of light conditions, unclear assessment criteria, varying levels of observer experience as well as their predisposition to underestimation or overestimation (Lick and Krapfenbauer 1986, Skelly 1992, Innes *et al.* 1993, Ghosh *et al.* 1995, Vacek *et al.* 1996). The constraints question the reliability of defoliation (estimated according to the ICP-Forest methodology) as a reliable indicator of the health of an individual tree or, more so, the health of the entire forest ecosystem. It has been empirically confirmed that there are statistically significant variations in the estimates of defoliation of the same trees at the same time by different teams of observers at a similar experience level (Innes 1988). Similarly, statistically significant differences in average defoliation index of the individual regional directorates of State Forests (administrative units of state-owned forests) were found between two independent research projects performed in Poland in 1991: biological monitoring and large-scale inventory of forest health condition (Lech 1995).

OBJECTIVES AND SCOPE OF THE STUDY

The objectives of the study were as follows:

1. To distinguish the indicators unsuitable for estimating tree health
2. To select the indicators most reliable and of highest diagnostic usability for estimating tree health
3. Definition of a normative health scale in terms of indicator values

To meet these goals, the measurements and analyses of the following biometric characteristics were made:

- tree crown defoliation,
- electric resistance of near-cambium tissues,
- biometric parameters of shoots and needles,
- dendrometric parameters, such as dbh, height and annual radial increment.

METHODS

Assumptions and Hypothesis

Von Bertalanffy's organismal theory and Hippocrates's correlation principle were the logical foundations for the hypothesis formulation. An organism is an integrated structure whose growth happens with the pre-defined trend of proportion changes between individual organs. The proportions between tree components, and the resulting (from them) proportions between the intensity of life processes, are expressed by specific relationships (interactions) between the parameters describing these processes or properties. This statement refers to both "healthy" and "ill" plants, because it cannot be assumed that the pathological course of one process influences other processes or brings about the changes only in the very place of its occurrence. This means, that for randomly selected trees, a positive relationship can be expected between the indicators characterized by the similar dependence to tree health, while a negative relationship can be expected between the indicators characterized by the opposite type of dependence.

These assumptions allow the formation of the following hypothesis:

> ***reliability and diagnostic usability of tree health condition indicators, characterizing a tree is most essential processes and features, are the same***

which should be expressed by the occurrence of statistically significant correlation between the indicators (a small number of indicator statistically significant dependencies with other indicators means poor reliability) and by the compliance of the nature of the relationships between the empirically measured indicators with the nature of these relationships defined *a priori* (no such compliance accounts for the lack of reliability).

Characteristic of the Study Sites

The study plots were located in the Karkonosze Mountains, at Szklarska Poręba forest district. The region is characterized by extreme ecological conditions, such as harsh climate, strong winds, air pollution, and poor and acidic soils (Jadczyk 1994). Forests growing there are usually Norway spruce stands often of unknown origin and unsuitable for local conditions (Wilczkiewicz 1982). The study was performed in three 60- to 70-year-old pure spruce stands in forest compartments 328, 84, and 86, at elevations of 650 m, 850 m, and 950 m above sea level and characterized by eastern, southwestern, and southern exposition. Measurements and samples were collected on all plots from a total of 110 trees in the stands differing in stocking, average dbh, and height of trees as well as in mean crown defoliation (table 1). During field trials in the period 1991-1994, no significant changes in these characteristics were observed.

Indicators of Tree Health Estimation and the Methods of their Evaluation

Seventeen coefficients of biometric characteristics of trees were tested to fulfill defined goals. They were as follows:

- Electric resistance of near-cambium tissues (Imp)
- Visually assessed crown defoliation (Def)

Dendrometric parameters

- Dbh (DBH)
- Tree height (H)
- Mean annual radial increment in periods 1981-85 and 1988-92 (Inc85, Inc92)

Indices of radial increment dynamics (change over time):

- stability (Stab = Inc92/Inc65)
- recovery (Rec = Inc92/Inc85)
- decline (Dec = Inc85/Inc65)

Biometric features of assimilative apparatus

- Mean length of shoot of the 1991 and 1992 sets (L91, L92)
- Mean dry mass of one needle of the 1991 and 1992 sets (M1_91, M1_92)
- Mean dry mass of needles per 1 cm of shoot of the 1991 and 1992 sets (M/1cm91, M/1cm92)
- Mean dry mass of needles per one shoot of 1991 and 1992 sets (M/shoot91, M/shoot92)

These characteristics directly or indirectly reflect the most vital processes and condition of a living tree, i.e., photosynthesis, transpiration, moisture level of near-cambium tissues and their nutrient status, damage to assimilation apparatus. Low costs and feasibility of measurement and analysis, in regard to the application possibility in the forest monitoring, have been the basis for indicator selection.

To evaluate tree health, the expected relations between the indicators and health have to be established. The relationship between tree health and the biometric parameters of assimilative apparatus (L91, L92, M1_91, M1_92, M/1cm91, M/1cm92, M/shoot91, M/shoot92) and the dendrometric features (DBH, H, Inc85, Inc92, Stab, Rec, Dec) has been assumed to be positive. On the other hand, the relationship between tree health and near-cambium electric resistance (Imp) or defoliation (Def) should be negative. If the above assumptions are true, then the dependence between the indicators within each of the two groups will be positive while the dependence between the indicators from different groups will be negative.

Statistical Analyses

A correlation analysis was applied to distinguish the indicators unsuitable for estimation of tree health. Then the cluster analysis that included indicators not eliminated in the preceding step was used to group similar trees, in respect of indicator values. Next, the one-variable analysis of variance (ANOVA) was applied to determine cluster-differentiating indicators. It was assumed that these indicators represent the highest reliability and diagnostic usability for health estimation among all tested parameters. Finally, the Scheffy confidence intervals for means from the plots of ANOVA selected indicators were combined for definition of a normative scale of tree health in terms of indicator values. It was done by extending the interval extremes to obtain continuous scale for every coefficient from health class 1 to health class 4.

Table 1.—*Characteristics of the study sites*

Attribute		**Plot**	
	328	**84**	**86**
Altitude above SL [m]	650	850	950
Aspect	Northeastern	Southwestern	Southern
Slope [%]	5-10	0-5	0-5
Stand age [years]	60-70	60-70	60-70
Stand density	Fully-stocked	Loosen	Intermittent
Range of defoliation [%]	20 – 75	10 - 65	25 – 85
Range of DBH [cm]	16.0 – 42.5	13.25 – 27.5	15.25 – 29.5
Range of tree's height [m]	18.2 – 27.1	13.0 – 21.4	12.6 – 16.8

RESULTS

The character (sign) of correlation between measured parameters, in most cases, agreed with the expected one. The only indicators of a greater number of contrary to assumption signs of correlation were the mean length of shoot of the 1992 set (L92) (6 cases on the plot 86 and 7 cases on the plot 328) and crown defoliation (Def) (5 and 1 such cases accordingly). Correlation signs different from the expected were also occasionally found for such indicators as M/shoot92, M/1cm92, M1_92, L91, and dbh. The signs of correlation of the remaining variables corresponded 100 percent to the assumptions. Contrary to assumption, character of dependence between indicators did not concern the pairs of indicators for which the correlation was statistically significant. It means that this discordance may be accidental and indicates the insufficiency of this criterion for the selection of reliable indicators of tree health.

The second criterion of the indicator selection was the number of statistically significant correlations between them (table 2). All indicators for which the average (of all the plots) number of statistically significant correlation dependencies was smaller than 8[1] (half of possible cases), or for which the number of these dependencies on any plot did not exceed 5.33[2], were subject to elimination. These were:

- Crown defoliation (Def)
- Mean length of shoot of the 1992 set (L92)
- Radial increment recovery index (Rec)
- Electric resistance of near-cambium tissues (Imp)
- Radial increment decline index (Dec)
- Dbh (DBH)
- Tree height (H)
- Mean annual radial increment in period 1981-1985 (Inc85)
- Mean length of shoot of the 1991 set (L91)
- Mean dry mass of needles per shoot of the 1992 set (M/shoot92)

Visually assessed defoliation, average shoot length of the 1992 set, radial increment recovery index, and electric resistance in near-cambium tissues were the variables for which the number of statistically significant correlation dependencies with other variables was smallest—equaled adequately 2.00, 3.33, 4.33, 4.67. On the other hand, the average annual radial increment in 1988-1992 (11.00), radial increment stability index (10.00), mean needle dry mass per 1 cm of the 1991 shoot (9.33), and the mean needle dry mass on the 1991 shoot (9.00), were the variables for which the number of statistically significant dependencies with other variables was greatest.

---

[1] *For Inc85, Dec, L91, L92, M/shoot91 and M/shoot92 it was 7.50 and for Rec – 7.00.*

[2] *For Inc85, Dec, L91, L92, M/shoot91 and M/shoot92 it was 5.00 and for Rec – 4.6.*

Table 2.—*The results of the correlation analyses*

Indicators	Number of significant dependencies between indicators				Result of selection
	Plot			Average	
	328	84	86		
Imp	9	2	3	4.67	-
Def	3	0	3	2.00	-
DBH	12	5	4	7.00	-
H	9	5	7	7.00	-
Inc85	12	5	4	7.00	-
Inc92	15	9	9	11.00	+
Stab	12	9	9	10.00	+
Rec	3	5	5	4.33	-
Dec	10	4	5	6.33	-
L92	2	5	3	3.33	-
L91	11	4	9	8.00	-
M1_92	11	7	8	8.67	+
M1_91	12	7	7	8.67	+
M/1cm92	11	6	9	8.67	+
M/1cm91	12	8	8	9.33	+
M/shoot92	9	7	7	7.67	-
M/shoot91	10	10	10	10.00	+

In the succeeding step, the cluster analysis was applied to group trees in respect to the similar health status, as expressed by values of remaining indicators: Inc92, Stab, M1_92, M1_91, M/cz92, M/cm91, and M/shoot91. To be in accordance with EC-UN/ECE classification, division on four clusters (health classes) was adopted. On plot number 84, due to obtained distances between clusters in the sequential steps, trees were arranged only into three groups. Then, the result of this classification served as a basis for one-way analysis of variance (ANOVA). It was performed to select the variables that determined the division of trees into health classes (clusters) (table 3).

Among seven indicators selected previously and used in this step, three did not differentiate trees between clusters. They were as follows: Inc92, Stab, and M1_92. The remaining four coefficients (M1_91, M/cm92, M/cm91, and M/shoot91) were characterized by statistically significant variability between almost all clusters and were acknowledged as most reliable among indicators tested in the study.

In the last step, the combination of Scheffy confidence intervals for means of four reliable indicators from the plots served as a basis for determining ranges of indicator values for health classes (table 4). Because only one tree

Table 3.—*Indicators differentiating clusters (health classes)*

Indicator	Plot data ANOVA			All data ANOVA	Reliability
	328	84	86		
Inc92	-	+/-	-	-	-
Stab	+/-	+/-	-	-	-
M1_92	+	+/-	+/-	+/-	-
M1_91	+	+/-	+	+	+
M/cm92	+	+	+/-	+	+
M/cm91	+	+	+	+	+
M/shoot92	+	+	-	-	-
M/shoot91	+	+	+	+	+

Reliability of a given indicator was assigned due to the ANOVA results:
"-" means lack of statistically significant differences between means from clusters
"+/-" means occurrence of statistically significant differences between means from some clusters
"+" means occurrence of statistically significant differences between means from all clusters

Table 4.—*Norway spruce health scale as expressed by indicators' value ranges*

Indicator	Health class	Plot 328		Plot 84		Plot 86		All data		Scale	
		MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX	MIN	MAX
	1			5.51	6.44	4.82	5.89	5.68	6.41	**> 5.0**	
M1_91	2	4.37	5.02	4.02	4.42	4.12	4.65	4.25	4.55	**4.1**	**5.0**
[g/1000]	3	3.45	4.23	3.17	3.57	3.69	4.14	3.49	3.79	**3.1**	**4.0**
	4	1.96	2.78			2.39	2.81	2.31	2.69	**≤ 3.0**	
	1			8.889	10.56	9.12	10.77	9.46	10.76	**> 9.0**	
M/cm92	2	8.16	8.94	7.41	8.14	7.98	8.81	7.88	8.423	**7.5**	**9.0**
[g/100]	3	5.97	6.90	5.45	6.18	6.38	7.08	5.97	6.514	**5.5**	**7.5**
	4	3.37	4.16			6.01	6.66	4.88	5.549		**≤ 5.5**
	1			10.36	12.05	11.10	12.96	11.54	12.76	**>10.0**	
M/cm91	2	9.11	9.96	8.44	9.17	8.43	9.36	8.79	9.27	**8.1**	**10.0**
[g/100]	3	6.73	7.74	6.38	7.11	6.87	7.66	6.76	7.27	**6.1**	**8.0**
	4	3.62	4.47			4.89	5.62	4.42	5.04		**≤ 6.0**
	1			0.857	1.027	0.795	0.926	0.877	0.970	**>0.70**	
M/shoot91	2	0.502	0.566	0.494	0.568	0.506	0.572	0.514	0.553	**0.46**	**0.70**
[g]	3	0.318	0.395	0.332	0.406	0.345	0.401	0.348	0.387	**0.31**	**0.45**
	4	0.157	0.221			0.233	0.285	0.205	0.252		**≤ 0.30**

was assigned to health class 1 on the plot number 328, the confidence intervals for this class were excepted. Similarly, the confidence intervals were omitted for the fourth health class on plot number 84 because of the three-class division of trees on this plot. As one may have noticed, in most cases the confidence intervals for respective health classes on plots overlap. Only for M1_92 was there a difference of values for the third health class between plots number 84 and number 86; for M/cm92 such a divergence was found for the second class between plots number 328 and number 84 and for the fourth class between 328 and 86. Other confidence intervals of indicator means for health classes were in a similar range, which enabled the grading of tree health as expressed by the values of selected indicators of a tree's biometric features.

DISCUSSION

The performed statistical analyses showed that the indicators tested in the study were characterized by different levels of reliability and diagnostic usability for estimating tree health. Crown defoliation appeared to be the least reliable indicator. The smallest number of statistically significant correlation dependencies with other indicators as well as the highest amount of discordance (with the assumptions) in sign of the relationship with other indicators manifested it. The highest reliability of assimilative apparatus biometric features indicates that the low reliability of defoliation is caused more by the method of its assessment than by a low diagnostic meaning of the symptom. Such an interpretation corresponds to the opinion of some authors (Innes 1988, Innes *et al.* 1995, Lech 1995), that the "weakness" of visually assessed defoliation is seen in the subjectivity of the way it is determined. On the other hand, among all indicators tested in the study, the most reliable and diagnostically usable were four parameters of assimilative organ features: M1_91, M/cm92, M/cm91, and M/shoot91. High numbers of statistically significant correlation dependencies with other indicators characterized them. In addition, the clusters' means from plots differed for them significantly.

It is interesting to note why the indicators referring to the 1991 set dominated among those selected as most reliable. From four such indicators, only one – average dry mass of needles per 1 cm of shoot of the 1992 set (M/cm92)—referred to the last set of needles and shoots. Explanation of that might be seen in strong juvenile shoot and needle growth dependence, especially in the early phase, on the status and photosynthetic effectiveness of the older needles. In Scots pine, it was found that the last but one set of needles participates in the tree high increment in 51 percent and in radial increment in 70 percent (Meixner and Wozniak 1981). For Norway spruce, similar values might be expected.

According to the results of the study, reliability and diagnostic usability of tested dendrometric parameters differed significantly. Two indicators—Inc92 and Stab—were the variables of the highest number (average for the plot) of statistically significant correlation dependencies with other variables among all those tested (11 and 10, respectively). However, as found in the analysis of variance performed after grouping trees into health classes (clusters), those indicators did not determine the division of trees. As such, both Inc92 and Stab were evaluated as inappropriate for estimating Norway spruce health. Other dendrometric parameters were found unreliable because of the low number of correlation dependencies with other indicators. Such a result is not surprising in the case of DBH, H, or Inc85. However, the low number of dependencies for Rec (Rec=Inc92/Inc85) – average for plot equal to 4.33, was not expected. It was assumed that this index should express the current vitality of the tree, as a manifestation of the ability to overcome the dramatic decline of growth observed in the Western Sudety during the first half of the 1980's. The increase of the radial increment rate in the second half of the 1980's and during the 1990's, which occurred in the stands where study plots were located, might not be an effect of the vitality and recovery ability of an individual tree. A favorable change in environmental conditions – reduction of stressing factor pressure (decrease in air pollution deposits) or the increase in insulation of needles, caused by lower density of crowns and stand stocking—can also serve as a probable explanation. The classification of dendrometric parameters as not reliable and of low diagnostic usability for evaluating tree health requires a comment. As a 5-year means, these parameters do not reflect the current status of a tree (i.e., from the moment other parameters were measured or assessed), but rather an averaged one. In the best case, for the mean year radial increment in the period 1988-1992 (Inc92), it was the 5 years preceding the collection of foliage, impedance, and defoliation data. The other dendrometric coefficients were even more outdated.

A similarity of value intervals of needle biometric parameters for almost all health classes on plots may be evidence of the existence of the universal scale of Norway spruce health condition. Such a scale might serve as a classification tool for estimating tree health and be applicable for all forest sites, climatic conditions, altitudes, etc. It should also be stressed here that the correctness of proposed coefficient value ranges for health classes needs to be tested in the next studies, performed in other places, in stands influenced by different stressing agents. If the values are confirmed, the scale will be ready for application in the monitoring of Norway spruce health.

CONCLUSIONS

1. The indicators used in the experiment are not of equal reliability and diagnostic usability for tree health estimation.

2. Least reliable variables were:
   - defoliation estimated according to the ICP Forest methodology
   - electrical resistance of near-cambium tissues
   - length of shoot of the last year set
   - DBH
   - tree height
   - average radial increment in the periods other than the last one.

3. The indicators of highest reliability and diagnostic usability for estimating of tree health were as follows:
   - mean dry mass of one needle, needles per 1 cm of shoot or needles per shoot of the last but one set (1991)
   - mean dry mass of needles per 1 cm of shoot of the last set (1992).

4. Establishment of a normative scale of tree health seems to be promising, but needs to be verified in additional studies.

ACKNOWLEDGMENT

The following people reviewed this manuscript: Professor Kazimierz Rykowski, Forest Research Institute, Department of Forest Ecology, Warsaw, Poland, and Dr. Jaroslaw Nowak, Philadelphia, MS, USA.

LITERATURE CITED

Ghosh, S.; Innes, J.L.; Hoffmann, C. 1995. Observer variation as a source of error in assessments of crown condition through time. Forest Science. 41(2): 235-254.

Innes, J.L. 1988. Forest health surveys: problems in assessing observer objectivity. Canadian Journal of Forest Research. 18: 560-565.

Innes, J.L.; Landmann, G.; Mettendorff, B. 1993. Consistency of observation of forest tree defoliation in three European countries. Environmental Monitor. Assessment. 25: 29-40.

Jadczyk, P. 1994. Przyczyny zniszczenia lasów w Górach Izerskich i Karkonoszach. I. Warunki środowiska i czynniki antropogeniczne. Sylwan. 12: 39-47.

Kandler, O. 1992. Historical declines and diebacks of Central European forests and present conditions. Environmental Toxicology Chem. 11: 1077-1094.

Lech P. 1995. Przydatnosc szacunkowej metody okreslania defoliacji drzew do badan stanu zdrowotnego lasu. Sylwan. 8: 99-109.

Lick, E.; Krapfenbauer, A. 1986. Terrestrische Waldzustandisinventuren und Probleme einer Objektivierung. Centralbl. Gesamte. Forstwes. 103.

Mayer, H.; Neumann, M.; Sommer, H.G. 1980. Bestandesaufbau und Verjüngungsdynamik unter dem Einfluss natürlicher Wilddichten im kroatischen Urwaldreservat Corkova Uvala/Plitvicer Seen. Schweiz. Z. Forstwes., Jg. 131: 45-70.

Meixner, J.; Wozniak, A. 1981. Przyrost wysokosci i grubosci mlodnika sosnowego przy zmniejszonym aparacie asymilacyjnym. Prace Kom. Nauk Roln. Lesn., T. 52: 109-113.

Mueller-Dombois, D. 1987. Natural dieback in forests. BioScience. 8: 575-583.

Mueller-Dombois, D.; Canfield, J.E.; Holt, R.A.; Buelow, G.P. 1983. Tree-group death in North American forests: a pathological problem or a new problem for vegetation ecology? Phytocoenologia. 11(1): 117-137.

Rykowski, K. 1984. Elektrometryczna metoda oceny stanu fizjologicznego sosny porazonej przez Armillaria mellea w warunkach nawozenia mineralnego. Prace IBL. 635: 81-103.

Schweingruber F.H. 1989. Lasst sich fechlends Datenmaterial zur Waldschadenssituation anhand von Postkarten erganzen? Allg. Forstz. 44: 266-268.

Sierota, Z. 1990. Biometrical features of needles of Scotch pine and Norway spruce under air pollution - a trial of verification of field assessment of crown transparency. Expertentagung Waldschadensforschung im Ostlichen Mitteleuropa und in Bayern. 13-15.11.1990, Schloss Neuburg/Inn bei Passau.

Sierota, Z. 1991. Biometryczne cechy aparatu asymilacyjnego jako posrednie kryterium oceny kondycji zyciowej sosny rosnacej w warunkach stresu. Sylwan. 4-6: 51-62.

Skelly, J.M. 1992. A closer look at forest decline: a need for more accurate diagnostics. In: Manion, P.D.; Lachance, D., ed. Forest decline concepts. American Phytopathological Society Press.

Soderberg, U. 1991. The relation between increment and defoliation for Scots pine and Norway spruce in Sweden. In: Proceedings of the IUFRO & ICP-Forests workshop on monitoring air pollution impact on pernament sample plots, data processing and results interpretation; 1991 September 2-6; Prachatice: 119-127.

Stachurski, A.; Zimka, J.R.; Kwiecien, M. 1994. Forest decline in Karkonosze (Poland). I. Chlorophyll, phenols, defoliation index and nutrient status of the Norway spruce (*Picea abies* L.). Ekol. Pol. 42(3-4): 289-316.

Trampler, T.; Dmyterko, E.; Kliczkowska, A.; Kludka, J. 1992. Wplyw stanu uszkodzenia na produkcyjnosc drzewostanów swierkowych. Project report (manuscript), IBL Warszawa.

Vacek, S.; Leps, J.; Stefancík, I.; Cicák, A. 1996. Precision of visual estimates of tree defoliation. Lesnictví-Forestry. 2: 49-53.

Waring, R.H. 1983. Estimating forest growth and efficiency in relation to canopy leaf area. Advanced Ecology Research. 13: 327-354.

Wilczkiewicz, M. 1982. Rys historyczny gospodarki w lasach sudeckich. Sylwan. 6: 49-54.

Wilmont, T.R.; Elsworth, D.S.; Tyree, M.T. 1995. Relationships among crown condition, growth and stand nutrition in seven northern Vermont sugarbushes. Canadian Journal of Forest Research. 25(3): 386-397.

Quality Control of Measurements Made on Fixed-Area Sample Plots

Ola Lindgren

Abstract.—The paper describes results from a large program for quality control of forest measurements. The performance of 87 surveyors was evaluated. Tree heights were usually measured well, whereas the counting of tree-rings on increment cores was a source of considerable bias for many surveyors. During tree count on sample plots, many surveyors had a tendency to forget trees, especially small trees. A conclusion of the study is that control surveys are justified. The control should be continuous during the field season, making it possible to detect inferior quality of work at an early stage.

This study was done to summarize the findings of control surveys that are regularly carried out and analyzed by our company. The forest surveys being checked were applications of field data collection for the Swedish "Forest Management Planning Package" (Jonsson *et al.* 1993). The original field data were collected from large forest holdings by a stratified multi-stage sampling design, using delineated stands as primary sampling units. Within each sample stand, 6 to 12 circular plots were laid out in a square grid pattern.

A survey of this kind typically estimates the growing stock with a sampling error of less than 3 percent at the forest holding level. It is therefore of interest to also estimate measurement errors, since they might have the same effect on the final estimates as the sampling errors. In addition, measurement errors don't always have an expectation of zero, which is the case for the sampling errors when an adequate probability sampling plan is applied.

By summarizing the performed control surveys, we are looking for answers to several questions. What are the characteristics of the measurement errors? How do different field surveyors compare in terms of quality of work? Are control surveys justified, or just a waste of money? If justified, how do we carry out the control program in the most efficient way?

THE DATA SET

The data set was derived from control surveys made during 1991-1997 within 10 different field projects. A total of 87 field surveyors were checked. The data consist of 2,523 fixed-area circular sample plots of radius 5-10 m, in which a total of 47,457 trees were measured by caliper. Several 3- to 10-m control plots were located in each of 529 randomly selected stands. Measurements of total tree height and age at dbh were controlled for 3,356 subsample trees. A small study of spatial accuracy in plot location was made on 46 sample plots.

The surveys were made in central and northern Sweden in forests dominated by Scots pine and Norway spruce. The conditions for measurement were generally favorable due to good visibility and flat terrain.

Regular as well as control surveys were carried out by surveyors working alone. Regular surveyors had at least a 2-year forestry education. They knew that a part of their work would be subject to re-measurement on a random basis. Control surveyors were well educated and experienced, and were allowed to work under less time pressure than the regular surveyors. Having more time available, the control surveyors calibrated their electronic instruments more frequently than the regular surveyors. A control surveyor would also bring difficult increment cores back to the office for counting tree rings by aid of simple optical devices.

Regular surveyors and control surveyors used the same types of instruments for the measurements. The Forestor DME (digital distance measurer) and steel tape (for calibration) were used to establish the plot boundaries. Tree diameters were measured by a Forestor 500 data caliper. Tree heights were generally measured by simple non-digital instruments from Suunto and Silva. The Forestor Vertex electronic hypsometer was used by regular surveyors in 1997 and by control surveyors during 1994-1997. The reader is directed to Jonsson (1991) for details about the electronic instruments being used. Traditional increment borers were used for extracting cores for counting tree rings. Simple optical devices were available to aid in the tree-ring count. All data were recorded directly into hand-held computers.

The data set was adjusted for growth that might have occurred between the time for the regular survey and the time for control survey. The control measurements were always made during the same field season as the regular measurements.

Consultant, OL Forest Inventory LTD, Köpmangatan 44 A, 83133 Östersund, Sweden. E-mail: ola.lindgren@olskog.se

ANALYSIS

Strictly speaking, we are not able to analyze true measurement errors, i.e., the differences between the measurements being recorded and the true values. For example, it is almost impossible to determine the true value of the basal area on a sample plot. It would be extremely time-consuming to get indisputable ground level references for each tree. Consequently, we are instead looking at differences between measurements made by the regular surveyors as compared to control measurements. The recorded measurements are furthermore affected by both "genuine" measurement errors and recording errors.

We have reason to believe that the measurements made by the control surveyors are practically bias-free. However, even the control measurements will have a random error component of the same magnitude, or somewhat smaller, than the regular measurements.

The analysis and presentation of the data for each variable focuses on the differences in the paired observations

$$d_{ij} = rm_{ij} - cm_{ij}$$

where rm = regular measurement
cm = control measurement
i = regular surveyor being controlled
j = item (tree, plot) being controlled

Mean values and standard deviations of the differences were calculated for the whole data set (pooled data) and for individual surveyors. By storing the statistics of the differences for individual surveyors, new data sets were created. In such a database, each case (record) refers to one of the 87 regular surveyors. The analysis of surveyor performance adds significantly to the results of this study. One can assess the proportion of low-performing surveyors needing extra attention. The results also constitute a benchmark test by which one can evaluate other surveyors working under similar conditions.

The mean difference in surveyor level is a measure of surveyor "bias" in relation to the control, whereas the standard deviation of the differences is a measure of the random component of the measurement error. The given standard deviations should be divided by the square root of 2 to express an approximate standard deviation of measurement errors in relation to true values (assuming random errors of the same magnitude in the control data set, and assuming independence between the respective random error components).

It is obvious that surveyor bias is an important criterion of measurement quality. But what about the random error component, doesn't it cancel out anyhow if only a sufficient amount of data is collected? Yes, but a large random error component will tend to hide bias because the estimated mean difference will be of poor precision, and statistical tests against zero will not be powerful. Furthermore, large random errors in variables such as tree age might result in biased growth predictions when using a growth function containing tree age.

Before comparing the statistics between surveyors, the mean differences and standard deviations were "normalized." This was done by re-expressing the statistics (of the differences) in percent of the surveyor level averages (according to control) of the respective tree or plot variable. This was necessary since different surveyors worked under somewhat different conditions of average tree height, basal area, and other variables.

RESULTS

Tree Height

Pooled Data

The mean difference of the whole data set was –0.26 dm, or –0.16 percent of the average tree height (157.7 dm). The standard deviation of the differences was 8.47 dm (5.4 percent of average tree height). There was no statistically significant bias in the pooled height measurements. Frequency tabulation showed that 84.5 percent of the trees differed by less than 1 m. The distribution of differences had somewhat larger tails than the normal distribution.

Results varied among species. For Scots pine, the regular surveyors underestimated the height by 0.75 dm, a mean difference significantly apart from zero (99.9 percent). For other species, heights were, on average, slightly overestimated. The standard deviation was largest for white birch (9.8 percent) compared with 4.6 percent for Scots pine and 5.7 percent for Norway spruce.

Figure 1 shows the differences in tree height plotted over tree height. The relation is unexpected; large differences occur quite frequently, also for low trees. This might be due to observation errors (wrong scale) or to recording errors.

Surveyor Performance

Figure 2 shows the results by surveyors, each point showing the measurement statistics for one single surveyor. On the x-axis, mean differences are shown expressed in percent of the average measurement of each surveyor. The y-axis shows the standard deviations of the differences, also expressed in percent of the average measurement of each surveyor. Markers show if the mean differences passed a 99 percent significance test (t-test) against zero (square) or not (cross). The number of

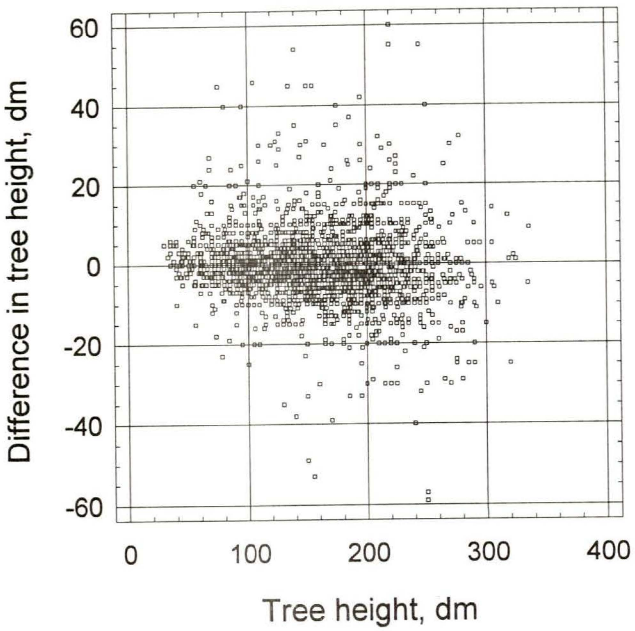


Figure 1.—*Differences in total tree height plotted against the tree height according to the control.*

observations behind each marker also influences the presence of statistical significance. The surveyors can roughly be divided into the following groups:

1. "The elite" is located close to the 0-line on the x-axis and in the lower part of the figure, indicating low bias and small random errors.

2. "Biased but consistent" are located away from the 0-line on the x-axis, but in the lower part of the figure. This group shows biased measurements, but because they are consistent it is possible to adjust for the bias, provided that a control survey is carried out.

3. "The tricky ones" are located in the upper part of the figure. A large random error makes it difficult to judge whether bias is present or not. If large bias is indicated, additional control data are often needed to determine if the members of this group need correction.

For tree height, 34 out of 87 surveyors showed significant (99 percent) differences compared to the control. The outcome was balanced: 18 had a negative mean difference and 16 had a positive mean difference. The magnitude of the bias is not large—on average, 4 dm or less than 3 percent of the average tree height. The massive appearance of statistically significant mean differences is due to the low random errors in height measurements. The surveyor with the largest bias had a mean difference of 7 percent (located in the upper right of the figure).

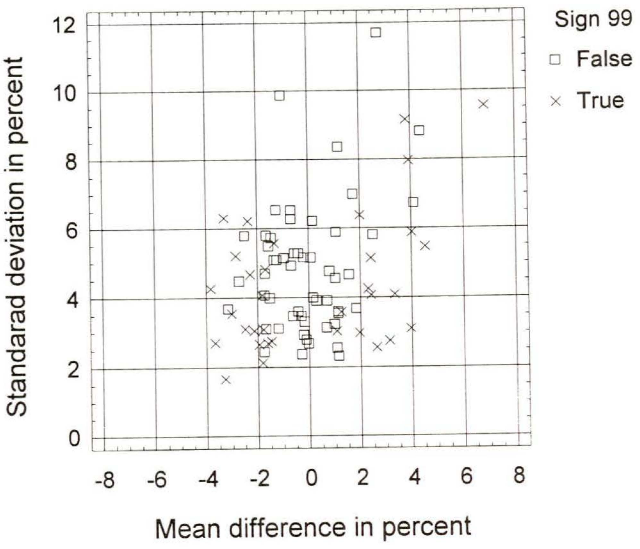


Figure 2.—*Evaluation graph for total tree height. Each marker shows the results for a single surveyor. Mean differences (x-axis) and standard deviations of the differences (y-axis) are expressed in percent of the surveyor level averages of tree height according to the control.*

Tree Age at Dbh

Pooled Data

The mean difference was –1.47 years, or –1.8 percent of the average age of 80.8 years at breast height. The standard deviation was quite large, 14.5 years (17.9 percent of average age). The underestimation of tree age is statistically significant (>99.9 percent). A frequency study showed that only 75.5 percent of the trees differed by less than 10 years. The tails of the distributions were large compared to a normal distribution.

On the species level, statistically significant underestimation was found for Scots pine (-1.3 years) as well as for Norway spruce (-2.0 years). The standard deviation was very large for white birch (35.0 percent) compared to Scots pine (14.9 percent) and Norway spruce (19.6 percent). Those results are consistent with the difficulties experienced by the surveyors when counting tree rings from different species in the field.

The relation between the age differences and age was quite expected. Up to age 80, differences were reasonably small, at least for the conifers. Large differences for conifers are almost always tied to old trees (the oldest trees in the data set were about 300 years old).

Surveyor Performance

Figure 3 shows the troublesome results of the tree age comparisons at surveyor level. Here, the group "the tricky

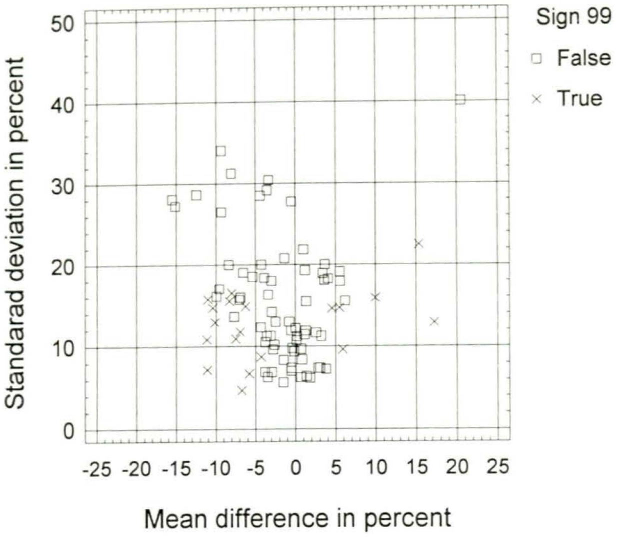


Figure 3.—*Evaluation graph for tree age (at dbh). Each marker shows the results for a single surveyor. Mean differences (x-axis) and standard deviations of the differences (y-axis) are expressed in percent of the surveyor level averages of tree age according to the control.*

ones" (cf. tree height above) is well represented. In the upper left and upper right of the figure, markers indicate surveyors with large random errors and possible large bias, but the bias indications are not statistically significant due to the large random errors. We do not have enough information to make the corrections that appear to be badly needed. In spite of the skewed distribution of mean differences, only 19 out of 87 mean differences are separated from zero with statistical significance. The magnitude of the bias (for the significant cases) is, on average, 6 years or about 9 percent.

Site Index

Pooled Data

Site indices for Scots pine and Norway spruce were estimated for each sample plot. The index H100 refers to the expected dominant height (in m) at total age 100. The most frequent method was to use site factors such as vegetation type, soil moisture, and elevation to estimate the index (Hägglund and Lundmark 1977). On plots with suitable conditions, site indices were also estimated with height development curves. Thus, the estimation of site indices required more of the subjective classification than other measurements described in this study. Consequently, the control measurements are also less "true."

The overall mean difference was 0.19 m, or 0.93 percent of the average index of 20.4 m. The standard deviation was 1.7 m (8.3 percent of average index). The slight overestimation was statistically significant. Frequency tabulation showed that over 80 percent of the plots differed by less than 2.0 m. A scatterplot showing the differences against the index itself (according to control) indicated that regular surveyors tended to overestimate low indices and to underestimate high indices.

Surveyor Performance

The evaluation plot in figure 4 shows a tight cluster of surveyors with non-significant mean differences and reasonable standard deviations. Some cases of significant bias are shown (15 out of 87 cases). Of those 15 cases, 13 have a positive mean difference, indicating overestimation of site index. The magnitude of the bias is just below 1 m, or 5 percent. A special analysis of the surveyors (with bias indication) showed that they sometimes had neglected index-reducing site conditions such as dry soil moisture or shallow soil depth.

Tree Count

Pooled Data

For this analysis, as well as for the following analysis of basal area, a filter was applied on the data set. Trees were defined as stems that are alive and having dbh of 5 cm or more. (In the actual data collection, both dead trees and trees below 5 cm were recorded.) Thus, differences in tree count are not only a result of classifying the trees as "in or out."

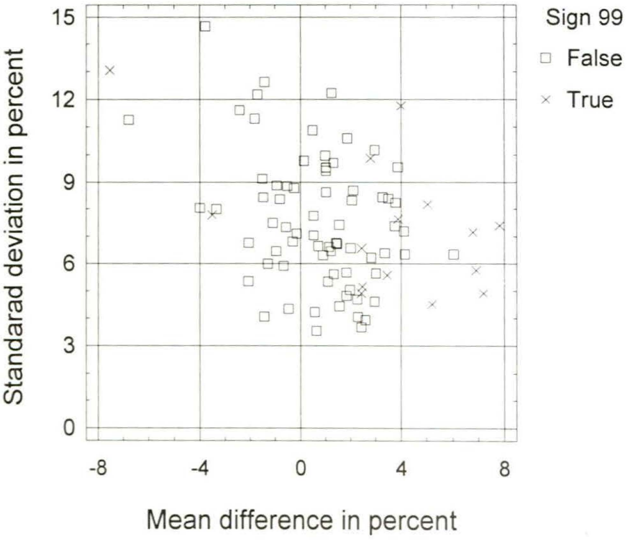


Figure 4.—*Evaluation graph for site index. Each marker shows the results for a single surveyor. Mean differences (x-axis) and standard deviations of the differences (y-axis) are expressed in percent of the surveyor level averages of site index according to the control.*

The mean difference was –0.52 trees per sample plot, or -2.8 percent of the average tally of 18.8 trees per plot. The standard deviation was 2.17 trees (11.5 percent of the average tally). The mean difference was separated from zero with very high statistical significance. If a difference in tree count is to occur, the sign of the difference is likely to be negative. Since each calipered tree is marked, cases of double-counting are rare. It is more likely to "forget" trees. According to the control surveyors, two types of trees are easy to forget: (1) trees near the plot boundary that surveyors are likely to classify as "out" without bothering to measure the distance, (2) trees very close to the plot center that are "left to take later," but are actually forgotten.

It is obvious that large differences in tree count require a certain number of trees on the plot. However, as soon as the tree number reaches 10, large differences begin to occur. Mean differences were computed separately for the different plot sizes applied (radius 5-10 m). The relation was not very strong. On the smallest (5 m) plots, 2.2 percent of the trees were missing (average count 12.4), whereas 3.0 percent of the trees were missing on the 10-m plots (average count 23.7).

Surveyor Performance

Figure 5 shows that the overall tendency to forget trees is not common for all regular surveyors. Most have a small mean difference, but the group with a statistically significant (99 percent) bias is quite large, 24 of 87 surveyors. Of those 24 with bias, 21 have underestimated the number of trees. The average bias in this group of 21 underestimating surveyors is –1.6 trees (-8.0 percent), a rather bad result. However, cases of large underestimation are generally statistically significant. There are a few cases (squares in the upper left of the figure) with a strong tendency to forget trees, but where the statistical tests are not powerful enough to verify the possible bias.

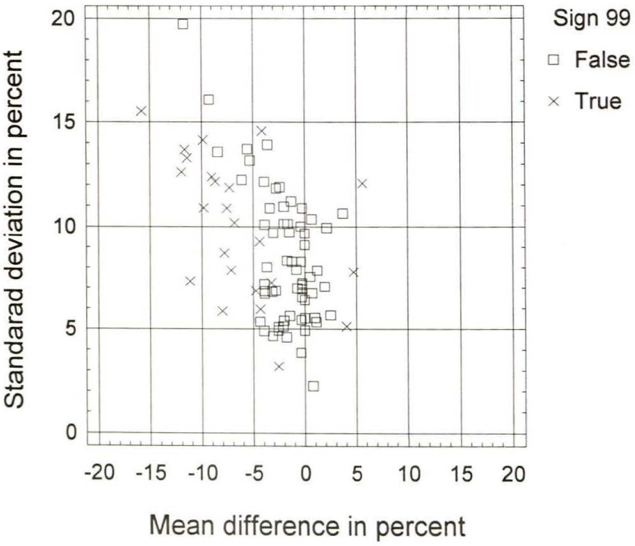


Figure 5.—*Evaluation graph for tree count. Each marker shows the results for a single surveyor. Mean differences (x-axis) and standard deviations of the differences (y-axis) are expressed in percent of the surveyor level averages of tree count according to the control.*

Basal Area Per Plot

Pooled Data

The basal area is expressed as dm^2 per plot. The mean difference was –0.276, or -0.7 percent of the average basal area of 41.5 dm^2. The standard deviation was 3.56 dm^2 (8.6 percent of average basal area). The slight underestimation of basal area is statistically significant (99.9 percent).

Looking back to the results for the number of trees per plot, 2.8 percent of trees were missing, whereas only 0.7 percent of the basal area is missing. One explanation for this is that small trees are forgotten more frequently than large trees are. Another explanation for the different results in tree count and basal area is that regular surveyors are overestimating the diameters. Unfortunately, the data set doesn't contain any pairwise data sets of single tree diameters.

An effort was made to estimate differences in diameter measurement by trimming the plotwise data set. A subset was made by selecting plots with (1) the same number of trees according to regular and control surveyors and (2) a difference (absolute value) between basal areas that was smaller than 5 percent of the basal area itself. The second condition was introduced to try to eliminate plots with different trees measured, although the tree count was the same. After trimming, the data set consisted of 962 plots (out of 2,523). The mean difference in basal area in the trimmed data set was –0.11 dm^2, or just –0.3 percent of the average basal area. This difference was only close to statistical significance at the 95 percent level. Since there was no strong evidence of differences in diameter measurements, one might find it likely that the difference between the results for tree count and basal area has another explanation. The conclusion is then that small trees are more easily forgotten than large trees. The control surveyors, who often made notes about careless treatment of small trees, support this conclusion.

Surveyor Performance

The individual results of basal area measurements are shown in figure 6. Most of the surveyors performed well. Nine surveyors had statistically significant mean differences (in relation to zero), seven of whom underestimated

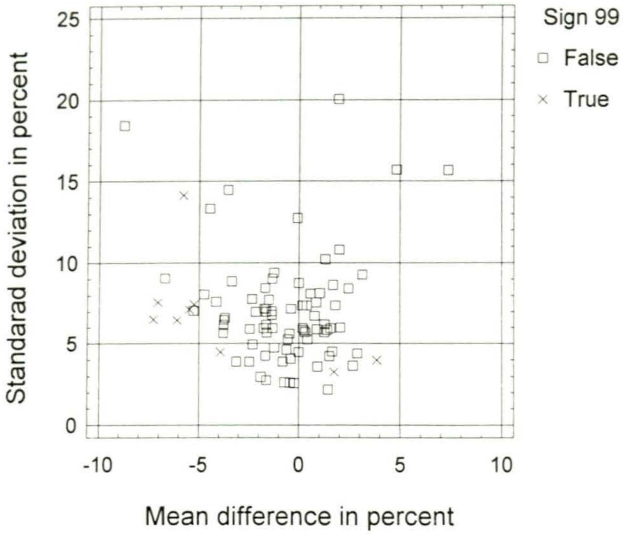


Figure 6.—*Evaluation graph for basal area per plot. Each marker shows the results for a single surveyor. Mean differences (x-axis) and standard deviations of the differences (y-axis) are expressed in percent of the surveyor level averages of basal area according to the control.*

the basal area. The average bias in this group of 7 is –5.8 percent, which is a serious level of bias.

The figure also shows quite a few surveyors with indication of bias, but this bias is not significant when exposed to a standard statistical test. More data would be needed to better evaluate this group.

Spatial Accuracy

The regular surveyors used a simple hand compass and a Haglöf Walktax distance measurer (thread) to lay out the sample plots. The distances from sample plots to roads or other distinct terrain features were within the range 0-300 m. However, the plots were not laid out independently. Plot 2 was usually laid out by measuring from plot 1 and so on.

A small study of spatial accuracy was made on 46 randomly selected control plots. The control surveyor was equipped with a Silva GPS recorder, using radio-transmitted real-time differential corrections giving a typical error of location of 2 m.

The average location error was 19 m, whereas the largest error was 41 m. The acceptable location error was specified to 30 m in the field manual. The study showed that 85 percent of the plots were located according to this norm.

The location error was positively correlated ($r=0.40$, $p=0.0056$) with the sequence number of sample plots within stands. Since the surveyors numbered their plots in consecutive order, this shows that the location errors are aggregating during the work within the stand. A significant positive correlation was also found between location error and the distance to road. However, some plots at roadside also had large location errors. This was found to be a result of misplacement of new roads on the map due to bad surveying practices.

CONCLUSIONS

The quality of field measurements made by different surveyors varied substantially. Serious levels of bias were present for about 10-20 percent of the group of 87 surveyors. In some cases, the bias was associated with small random errors, making it possible to calibrate the regular measurements. In other cases, the analysis indicated severe bias, but random errors were too big to make it possible to estimate the level of the bias with reasonable accuracy. The following conclusions can be drawn from this synthesis of surveyor performance:

1. Control surveys are justified. In some field projects, the bias resulting from measurements had a magnitude that was greater than the standard error due to sampling. In other field projects, the control survey only verified the good quality of the regular measurements. But that is also a valuable finding. The important thing is that the measurement errors are under control. Furthermore, the very existence of a control survey is judged to have a positive effect on the quality of field work.

2. There is a need for improved training of the surveyors before the work is started. Even experienced foresters have to be trained in the art of accurate measurement.

3. It should be possible to detect potential problems at an early stage of work. This is to avoid the situation when the "tricky cases" (indication of severe bias in connection with large random errors) are discovered after the end of the field season. Early detection will make it possible to give the surveyor additional training or at least to collect more control data before winter comes.

4. The "evaluation graphs" (figs. 2-6) can be used as a benchmark test when a first set of control data is analyzed. Depending on the outcome, the control fraction can be increased for the surveyors showing signs of inferior work.

Finally, some comments need to be made on the use of new instruments. The introduction of electronic hypsometers has not yet made any measurable effect on the quality of height measurements in our control program. Improving the ability to make accurate readings from a given location on ground is, of course, an advantage. However, the actual choice of location for making the measurement affects the final measurement quite a bit, as compared to the formal accuracy of reading as given in the technical specifications for the instruments. When electronic hypsometers are used, instrument-specific bias may occur due to erroneous calibration or other technical malfunctions. It might be easier to detect a malfunction in a simple device. It is strongly recommended that all kinds of hypsometers be checked on a regular basis by measuring objects with known heights, such as flagpoles or buildings.

Some preliminary trials comparing different types of calipers have shown substantial differences in diameter readings, even when the breast height location and the measurement direction are fixed. A routine analysis of a control survey made us aware of this problem.

ACKNOWLEDGMENTS

The author thanks the clients who made their field data available to this study and the personnel who did the field work. The following people reviewed this manuscript: Torleif Carlsson, The Forestry Research Institute of Sweden, Uppsala, Sweden; Göran Kempe, Swedish University of Agricultural Sciences, Department of Forest Resource Management and Geomatics, Umeå, Sweden; and Göran Ståhl, Swedish University of Agricultural Sciences, Department of Forest Resource Management and Geomatics, Umeå, Sweden.

LITERATURE CITED

Hägglund, B.; Lundmark, J.-E. 1977. Site index estimation by means of site properties. Studia Forestalia Suecica 138.

Jonsson, B. 1991. Electronic instruments and computerized devices in forest management planning. Report 23. Swedish University of Agricultural Sciences, Section of Forest Mensuration and Management. 20 p.

Jonsson, B.; Jacobsson, J.; Kallur, H. 1993. The forest management planning package. Theory and application. Studia Forestalia Suecica 189. 56 p.

Modeling Variability and Scale Integration of LAI Measurements

Kris Nackaerts and Pol Coppin

Abstract.—Rapid and reliable estimation of leaf area at various scales is important for research on chance detection of leaf area index (LAI) as an indicator of ecosystem condition. It is of utmost importance to know to what extent boundary and illumination conditions, data aggregation method, and sampling scheme influence the relative accuracy of stand-level LAI measurements. This knowledge should lead to a high repeatability and relative accuracy of the LAI measurements. In this research, LI-COR is recorded with a Licor LAI-2000, one of the more modern and widely used plant canopy analyzer instruments. The impact of external factors (boundary and illumination conditions) is minimized by means of a viewcap. The impact of sampling scheme and data aggregation method on the relative accuracy of the retrieved stand-level LAI value is quantified by means of Monte Carlo simulation.

In studies of the Earth's ecosystems, leaf area index (LAI) plays a prominent role as an indicator of the ecosystem condition at various scales. In the past decades, much attention has been given to the simplification and optimization of biophysical attribute measurement techniques (Goel and Norman 1990). At almost the same time, information content of multispectral satellite imagery has been studied, confirming its usefulness for large-scale quantitative assessment of biophysical attributes such as LAI. Most of these activities concentrate on model development and calibration, defining the relation between field inventory LAI data and remotely sensed vegetation indices (Carlson and Ripley 1997, Price and Bausch 1995).

LAI can be assessed directly by destructive sampling or litter traps. But this type of sampling is time consuming, labor intensive, and not compatible with long-term ecosystem monitoring. Different indirect measurement techniques have been developed and commercialized, speeding up LAI assessment considerably in a non-destructive way. The LI-COR LAI-2000 plant canopy analyzer (PCA) is an example of these techniques and will be used in this study.

However, indirect LAI measurements are liable to different types of errors. Inaccuracies are induced by both external and internal factors. Weather or illumination conditions and boundary effects are external factors, not related to characteristics of the element of interest (forest canopy). Sampling scheme (design and intensity), data aggregation method, and measurement errors caused by imperfections and simplifications of the foliage distribution model, which assumes a random distribution of foliage in the canopy, are considered as internal factors.

Most scientific literature focuses on the calibration of retrieved LAI-values due to a non-random distribution of foliage at different scales. Smolander *et al.* (1994) and Stenberg (1996) discuss the impact of foliage clumping at the shoot level for conifers. The ratio of the mean shoot silhouette area to total needle area has been proposed as the calibration factor for LAI-2000 PCA measured LAI values. The assessment of the mean shoot silhouette area is rather labor intensive and the calibration factor is highly dependent on stand characteristics such as age and species composition. Chen and Cihlar (1995) studied the effect of canopy architecture on optical LAI measurements. A new instrument has been developed to assess the gap-size distribution used to calculate the element-clumping index, which quantifies the effect of non-random spatial distribution of foliage elements. This index is then used as a calibration factor for the LAI value measured with the LAI-2000 PCA. The labor-intensive characteristics and high costs of these methods limit their application.

Up until now, the impact of a data aggregation method and sampling scheme–necessary to relate data of different topological dimensions-on the accuracy of the estimated LAI has not been investigated well. However, data aggregation is an inevitable step in observations where point-level field data are related to area- or pixel-level remotely sensed data. The confidence limits of stand-level LAI values play a prominent role in quantitative change detection, because they define the accuracy of the monotemporal reference data. What is more, no elements outside the area of interest (e.g., forest stand) should be drawn into the measurement of a site-specific LAI value.

Research Assistant and Professor of Spatial Data Sciences, respectively, Laboratory for Forest, Nature and Landscape Research, KULeuven, Vital Decosterstraat 102, 3000 Leuven, Belgium.

This is of utmost importance when the information content of medium resolution imagery is related to biophysical attributes of highly fragmented and/or small-scale natural communities, as is the case in the study area. The impact of the external factors (illumination conditions and boundary effects) is minimized. The impact of a sampling scheme with integrated data aggregation method is quantified. An adequate sampling design and minimal sampling intensity (minimize field labor) is defined based on a selected acceptable relative accuracy with respect to the assessed stand-level LAI.

The present study is part of an ongoing research project on the modeling of LAI as a scale-integrated indicator of vitality and biodiversity in Flemish forest communities. An accurate detection and quantification of change or a high relative accuracy of monotemporal LAI data is therefore of utmost importance.

MATERIALS AND METHODS

Instrument Description

The LAI-2000 PCA consists of five sensors, each measuring light intensities ((< 490 nm) over five concentric FOV's centered on 7, 23, 38, 53, and 68 degrees zenith, referred to as sensor 1, 2, 3, 4, and 5, respectively. Simultaneously acquired above- and below-canopy readings are combined to calculate overall LAI using the equation (LI-COR 1992)

$$LAI = -2\int_{0}^{\pi/2} \ln(T(\theta))\cos\theta\sin\theta d\theta \qquad [1]$$

where

$T(\theta)$ = canopy gap fraction
θ = zenith angle

This formula can be converted to

$$LAI = 2\sum_{i=1}^{5} K_i W_i \qquad [2]$$

where

$$K_i = -\frac{\ln(T(\theta_i))}{S(\theta_i)} \qquad [3]$$

$$S_i = 1/\cos\theta_i \qquad [4]$$

$$W_i = \sin\theta_i d\theta_i \qquad [5]$$

K_i or contact frequency combines the more measurable terms ($T(\theta_i)$ is computed out of the LAI-2000 PCA readings) and is equivalent to the average number of contacts per unit length of travel that a probe would make passing through the canopy at zenith angle θ_i. A random distribution of foliage in the canopy is assumed. Because the light intensity below a forest canopy is influenced not only by foliage but also by all structural elements of a canopy, the Vegetation Area Index (or VAI) better describes the measured attribute.

Experimental Design

A reference data set was constructed for the study area (Pijnven) located near Hechtel (Belgium). The test site can be described as a uniform, even-aged Corsican pine (*Pinus nigra var. Corsicana*) stand, measuring 150 by 150 m. The average canopy height is 20 m. The reference sampling scheme is based on the relation between the FOV of the sensors (without viewcap) and the canopy height. To minimize data redundancy, overlapping FOV's are avoided. The minimum spacing between sampling points is determined by equation [1] for sensor 1, corresponding to the smallest FOV and equals approximately 10 m. A regular grid design oriented according to the geometry of the test site results in concatenating FOV's covering the whole stand. Contact frequencies are assessed with the LAI-2000 PCA in all sampling points. Data acquired outside the internal area (see below) for a given sensor are influenced by elements beyond the area of interest and will not be retained for further analysis.

Theoretical Background

Illumination Conditions

As mentioned in literature (Welles 1990), direct sunlight is an important cause of variability in VAI measurements with the LI-COR LAI-2000. To increase the number of measurement days, the impact of direct sunlight is minimized. The use of a viewcap of at least 180° (oriented to north) prevents direct sunlight from the FOV. To quantify the impact of direct sunlight on the measured contact frequencies for different zenith angles, a random uniform black and white pattern printed on a transparency was used to simulate a forest canopy. Contact frequencies were measured below the simulated canopy on a clear day. This was repeated 20 times for random canopy orientations. The relative accuracy, defined as:

$$1.96 \times \text{StDev} / \text{Mean} \qquad [6]$$

was calculated for all sensors covered with different viewcaps (no viewcap, 180° FOV, 90° FOV; FOV oriented to north).

Boundary Effects

It is evident no elements outside the area of interest should be drawn into the measurement of a site-specific VAI value. The influence of elements outside the area of interest is minimized by the use of a 270° viewcap resulting in an effective FOV of 90° combined with an adequate sampling design. Taking the geometric properties of the FOV of each sensor of the PCA into account, the internal area not influenced by external elements can easily be defined for each sensor given the canopy height and site orientation. The maximal radius of the FOV at the canopy top can be calculated for each sensor

$$R = H \times \tan(\alpha) \qquad [7]$$

with

H: mean canopy height
α: maximal zenith angle of the FOV of the sensor

For a square test site with a western deviation from north of β ($\beta \leq 45°$), the minimal orthogonal distance to the site boundaries can be calculated as (fig. 1):

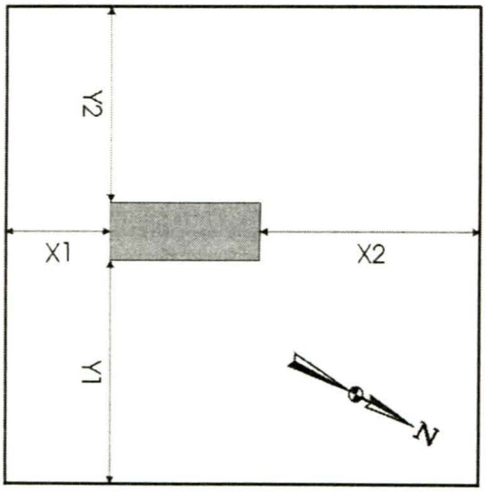


Figure 1.—*Geometric properties of the sensor-specific internal area of a square test site.*

$$Y_1 = R \times \sin(45° + \beta) \qquad [8]$$

$$Y_2 = R \times \sin(45° - \beta) \qquad [9]$$

$$X_1 = 0 \qquad [10]$$

$$X_2 = R \qquad [11]$$

The same equations can be used for a square test site with an eastern deviation from north of β' ($\beta' \leq 45°$) with

$$\beta = -\beta' \qquad [12]$$

This ensures no elements outside the test site are taken into account when measuring site specific LAI's.

Aggregation Method

A stand-specific contact frequency is estimated for each sensor individually, assumed to be representative for the whole stand. For this, data are assessed only from within the internal area of a given sensor. This means that when a sampling point is located near the border of a stand, only data from the inner sensors will be used. For sampling points near the center of the stand, data from the outer sensors will also be included. The average of the retrieved contact frequencies for a given sensor is used as a stand-specific estimation of the contact frequency of the respective sensor. The stand-level VAI value is calculated out of the acquired contact frequencies for the five sensors by equation [2].

Quantification of the Impact of the Sampling Scheme

The quantification of the impact of sampling scheme and data aggregation method on the relative accuracy of the estimated VAI value is modeled by a Monte Carlo simulation of point-level contact frequencies for each sensor individually. This requires detailed information on the local and spatial variability of the contact frequencies for all sensors. The local variability of the contact frequency readings is modeled using basic statistical tools. Correlation between contact frequency data of adjacent sensors is expected due to a vertical overlap of the FOV's of both sensors and explored with standard regression techniques. Spatial auto-correlation is assumed to be negligible at the scale of the test site (relevant for most forest stands in Belgium) when the extent of the field of view of the sensor is taken into account.

A Monte Carlo simulation of point-level sensor-specific contact frequencies is applied to generate independent data sets with the same statistical characteristics as the reference data set. This can be interpreted as a simulation of different forest stands with the same LAI.

Due to the assumed absence of spatial auto-correlation, the sampling design only determines sampling intensities for each sensor. Different realistic sampling schemes with intensities ranging from 131 (maximum internal area points for sensor 1) to 1, are applied on point-level sensor-specific simulated contact frequencies. Point-level sensor-specific contact frequency data are simulated by means of a self-written program (the original or executable code can be obtained from the corresponding author). This point-level information is aggregated so that each simulation results in one stand-level VAI value, which can then be considered as an independent sample of the population describing the "real" stand-level VAI value. A population is simulated for each design. The relative accuracy (corresponding to the confidence interval at a significance level of 5 percent) is cross-referenced against the number of sampling points, and a function is graphically fitted to this relationship. The minimum number of simulations is defined by a pre-determined acceptable R^2 for the fitted regression function. An R^2 of 90 percent is considered acceptable.

RESULTS AND DISCUSSION

Illumination Conditions

In figure 2, the relative accuracy of the measured contact frequencies is plotted for the five different sensors of the PCA for three different viewcaps. The relative accuracy is comparable for most sensors for different viewcaps. Only for sensor 3, a large significant difference (at a 0.05 significance level) exists between the accuracy of contact frequencies measured with and without a viewcap. This high variability causes a decrease in relative accuracy of the calculated LAI from approximately 5 percent when a viewcap (180° or 270° viewcap) is used to little more than 20 percent when no viewcap is applied.

The high variability of the sensor 3 readings can be explained by the effect of direct sunlight. At the moment of data acquisition, the sun was located at an average elevation angle of 50°, falling only in the FOV of sensor 3 (ranging from 47° to 58°-zenith angle) when no viewcap is applied. The sun is thus continuous in the FOV of sensor 3 on the instrument acquiring above-canopy readings. High fluctuations in measured light intensities caused by not blocked, or partly or completely blocked direct sunlight in sensor 3 are responsible for the high variability in the calculated contact frequencies for this sensor. When the sun is not blocked or partly blocked, the canopy in the FOV is partly overexposed, resulting in an underestimation of LAI values. This is illustrated by figure 3. A 180° or 270° viewcap is required to minimize the impact of direct sunlight on assessed VAI values as demonstrated.

Boundary Effects

Given an average height of 20 m and a western deviation from north of 28° for the test site, the internal area is defined by equations [8], [9], [10], [11]. Calculated values for the 270° viewcap are shown in table 1.

The impact of the 270° viewcap on the extent of the internal area relative to other viewcaps is visualized for sensor 5 in figure 4. Sensor-5 measurements inside the specified area are not influenced by elements outside the test site. With no viewcap, this area is more than 40 times smaller than when the 270° viewcap is used.

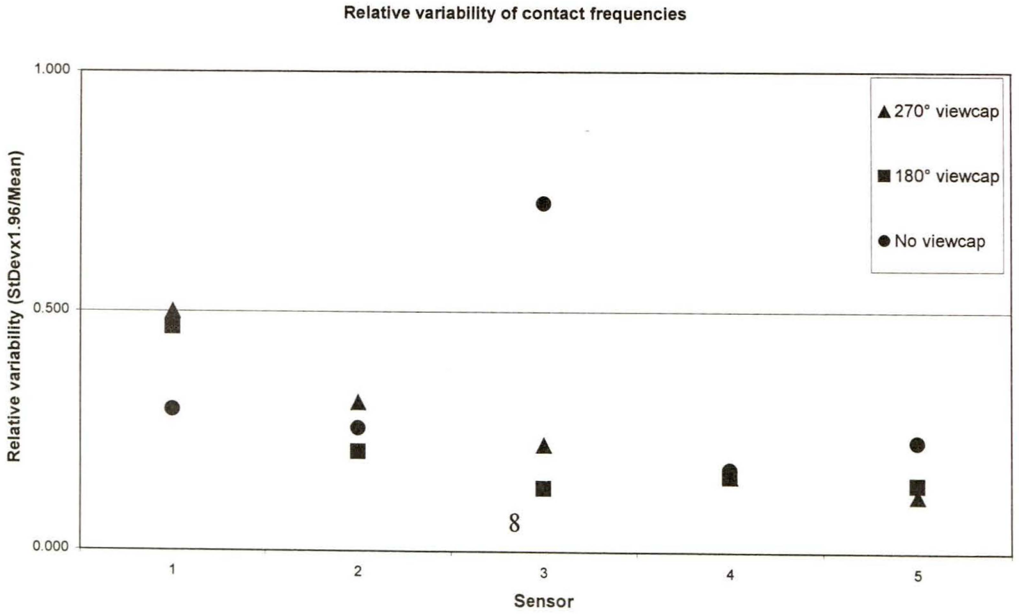


Figure 2.—*Relative variability of contact frequencies for different viewcaps under clear sky conditions.*

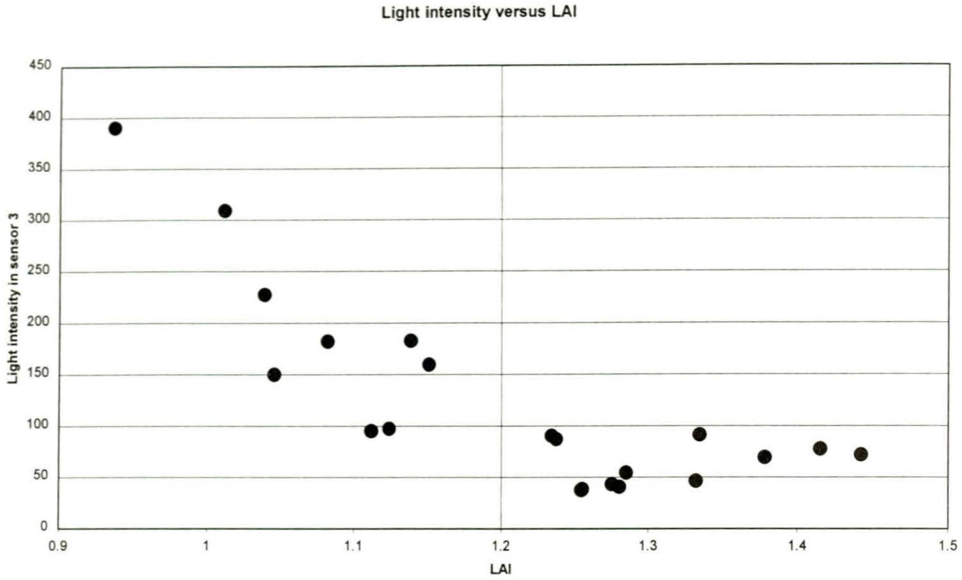


Figure 3.—*Impact of direct sunlight on LAI measurements.*

Table 1.—*Geometry of the internal area for the 270° viewcap with an eastern declination of 28°*

Sensor	Max zenith angle of FOV	R	X1	X2	Y1	Y2
	Degree	- - -	- - -	- *m* -	- - -	- - -
1	13	5	0	5	4	1
2	28	11	0	11	10	3
3	43	19	0	19	18	5
4	58	32	0	32	31	9
5	74	70	0	70	67	20

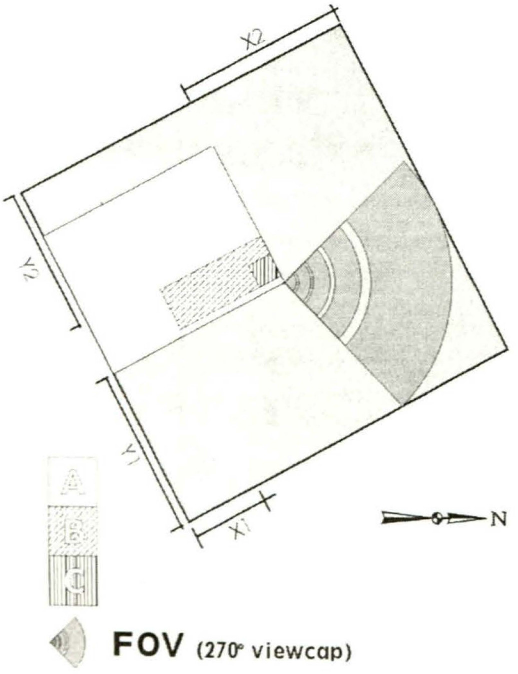


Figure 4.—*Internal area for different viewcaps with respect to sensor 5. Viewcaps: A: 270°; B: 180°; C: none*

Quantification of the Sampling Scheme and Integrated Aggregation Method

Modeling of Contact Frequency

Contact frequencies were sampled on a regular grid (10-m spacing) covering the whole test site (150 by 150 m). Taking the internal area of each sensor into account, 132, 110, 110, 81, and 24 samples for sensor 1, 2, 3, 4, and 5, respectively, were retained. A weak but significant correlation was found between contact frequencies of adjacent sensors with an average R^2 of 20 percent and normally distributed residuals. Due to the low exploratory characteristics of the assessed correlations, the distribution of the contact frequencies was also analyzed without taking the correlations into account. Contact frequencies are normally distributed for each sensor and can thus be described by the mean and standard deviation (see table 2).

Table 2.—*Parameters describing the distribution of contact frequencies for each sensor*

Sensor	Mean	Standard deviation
1	0.94	0.48
2	0.85	0.24
3	0.89	0.15
4	0.87	0.08
5	0.78	0.05

Simulation of Contact Frequency

Contact frequencies were simulated based upon the retrieved statistical information of the reference data set. Taking the correlation of contact frequencies between adjacent sensors into account did not result in significantly different simulated VAI values with respect to values simulated without this characteristic, as could be expected due to the low explanatory characteristics of the correlation as mentioned before. For this reason, contact frequencies were assumed not correlated in further analysis.

The confidence limit of the simulated VAI values is plotted for different sampling schemes against the sampling intensity. A power function was fitted through these data with Microsoft Excel and R^2 was calculated. This was repeated for different numbers of simulations. The lower the number of simulations, the higher the variability of the calculated confidence limit and the lower the R^2 of the fitted regression function as illustrated in table 3.

Table 3.—*R^2 of the fitted regression function describing the relation between sampling intensity and relative accuracy of estimated VAI*

Number of simulations	R^2
5	0.60
10	0.72
20	0.89
50	0.93
100	0.91
500	0.97

Based on the retrieved information, it was decided to use 50 simulations. Figure 5 illustrates the impact of sampling intensity on the accuracy of the retrieved VAI values.

Because no spatial autocorrelation is modeled, the sampling design influences only the number of internal area sampling points for each sensor. Different sampling schemes with the same sampling intensity having different orientations may thus result in a different relative accuracy of the retrieved VAI values, as can be seen in figure 5 (e.g., sampling intensity of 36). This relatively small difference is caused by the different orientation of the designs, resulting in differences in the number of internal area points with respect to each sensor individually. For example, two regular-grid sampling schemes were applied with an intensity of 36 sampling points. Due to their different orientation, 36, 30, 30, 25, and 6 internal area sampling points were retained for sensor 1, 2, 3, 4, and 5, respectively, for one design, and only 36, 25, 25, 20, and 6 internal area sampling points were retained for sensor 1, 2, 3, 4, and 5, respectively, for the other.

Based on a pre-defined acceptable relative accuracy of 10 percent and the variability caused by the design, it was decided to use 16 sampling points to estimate stand-level VAI. Due to ergonomic considerations, a regular grid design was selected.

ACKNOWLEDGMENTS

We thank the following two reviewers for their constructive comments: Marvin Bauer, Professor of Remote Sensing, Department of Natural Resources, University of Minnesota, St. Paul, MN, USA, and Bart Muys, Assistant Professor of Forestry, Department of Land Management, Catholic University of Leuven, Leuven, Belgium.

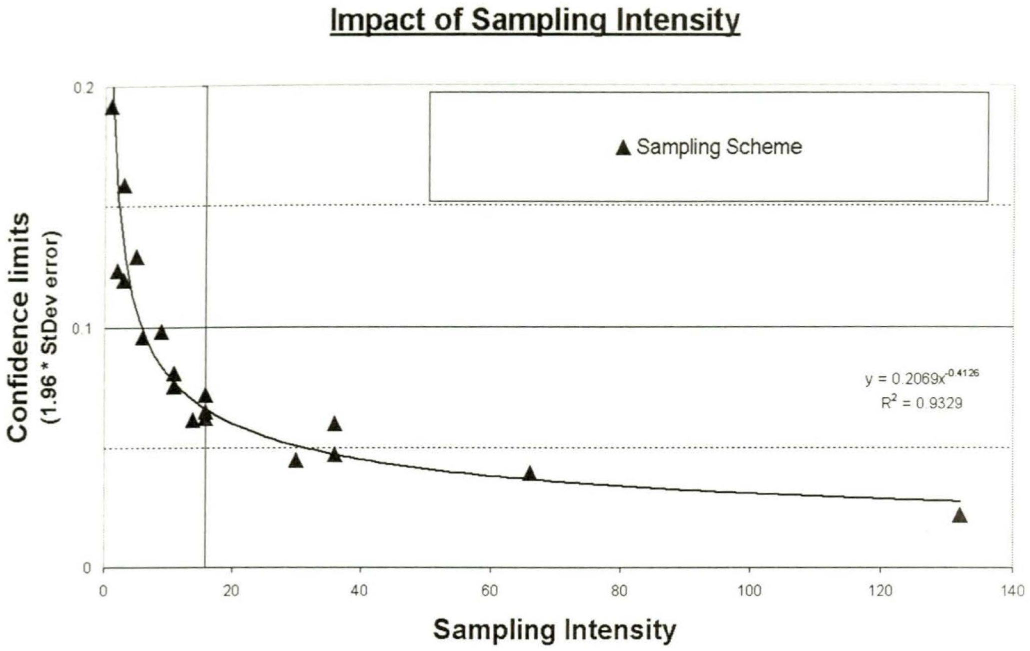


Figure 5.—*Impact of sampling intensity on the relative accuracy of retrieved VAI.*

LITERATURE CITED

Carlson, T.N.; Ripley, D.A. 1997. On the relation between NDVI, fractional vegetation cover, and leaf area index. Remote Sensing of the Environment. 62: 241-252.

Chen, J.M.; Cihlar, J. 1995. Quantifying the effect of canopy architecture on optical measurements of leaf area index using two gap size analysis methods. IEEE Transactions on Geoscience and Remote Sensing. 33 (3): 777-787.

Goel, N.S.; Norman, J.M. 1990. Instrumentation for studying vegetation canopies for remote sensing in optical and thermal infrared regions. In: Remote Sensing Reviews. 5(1). Reading, UK: Hardwood Academic Publishers. 360 p.

LI-COR. 1992. LAI-2000 plant canopy analyzer: instruction manual. Lincoln, NE: LI-COR, Inc.

Price, J.C.; Bausch, W.C. 1995. Leaf area index estimation from visible and near-infrared reflectance data. Remote Sensing of the Environment. 52: 55-65.

Smolander, H.; Stenberg, P.; Linder, S. 1994. Dependence of light interception efficiency of Scots pine shoots on structural parameters. Tree Physiology. 14: 971-980.

Stenberg, P. 1996. Correcting LAI-2000 estimates for the clumping of needles in shoots of conifers. Agricultural and Forest Meteorology. 79 (1-2): 1-8.

Welles, J. 1990. Some indirect methods of estimating canopy structure. In: Norman, J.; Geol, N., eds. Instrumentation for studying vegetation canopies for remote sensing in optical and thermal infrared regions (Hardwood, London,): 31-43.

Mathematical Form Models of Tree Trunks

Rudolfs Ozolins

Abstract.—Assortment structure analysis of tree trunks is a characteristic and proper problem that can be solved by using mathematical modeling and standard computer programs. Mathematical form model of tree trunks consists of tapering curve equations and their parameters. Parameters for nine species were obtained by processing measurements of 2,794 model trees and studying the variability of 53,000 relative diameters.

Tapering tables comprise a large number of tree trunk dimensions, which are not convenient to handle even by advanced computers. The idea of taking advantage of empirical formulas as a compact storage of information is not new. A project for the creation of mathematical tapering table models was accepted at the Latvian Forest Inventory Institute 25 years ago. Basically this research work was completed in 1982. At present, investigations are continuing in different directions. A program for producing variable assortment tables was developed by the author of this paper and approved at the Latvian Forestry Research Institute "Silava." During the last few years, diverse simplified versions of variable tables have been applied in Latvia as official state standards.

METHODS

Methods used for this study can be divided into two groups. The first group includes some widely used statistical methods. The second group contains original, not ordinary, methods: hyperbolical interpolation, designing of empirical formula by linear transformation, perturbation of relative diameters, generation of variable assortment tables, designing of round wood volume formulas, and other methods. These methods can be useful in forest research.

Hyperbolical Interpolation

The intention to use the equation of hyperbola for smoothing the connection between the thickness and height of a tree for the first time was approbated in 1968. Advantages of hyperbola as compared to classical parabolical interpolation for the approximation of monotonous values proved to be obvious. Measurements of model trees are necessary information for designing the tapering curve equation. Rough data were collected from different places in Latvia by different methods over several years. The first stage of primary information processing was the computation of actual diameters by using hyperbolical interpolation (form. 1):

$$d = d_1 + \frac{h-h_1}{k(h-h_1)+c}, \quad \text{where}$$

$$c = \frac{\dfrac{1}{d_2-d_1} - \dfrac{1}{d_3-d_1}}{\dfrac{1}{h_2-h_1} - \dfrac{1}{h_3-h_1}};$$

$$k = \frac{1}{d_2-d_1} - \frac{c}{h_2-h_1} \qquad (1)$$

The conventional signs used are:

h_1, h_2, h_3—distances from the butt-end to the given cut, m;

d_1, d_2, d_3—actual corresponding diameters, cm;

h—distance from the butt-end to a freely selected cut, m;

d—actual calculated diameter, cm.

If $h_1 < h_2 < h_3$, then h can be selected from the interval fixed by inequality $h_1 < h < h_3$. Extrapolation is not permitted.

Designing of Empirical Formulas by Linear Transformation

Actual diameters are usually estimated in different places of a tree trunk, beginning from the butt-end with a step of 2 m. In total, results of measuring can be displayed as the tapering curve or side-face of the model tree. For instance, if tapering curves of 15 birch trunks with diverse parameters or dimensions are drawn in one picture, a sufficient chaotic crossing of different broken lines can be obtained. It is impossible to notice any connection (fig. 1).

Professor of Mathematics, Dr. habil. silv., Latvia University of Agriculture, Liela iela 2, Jelgava, LV3001, Latvia.

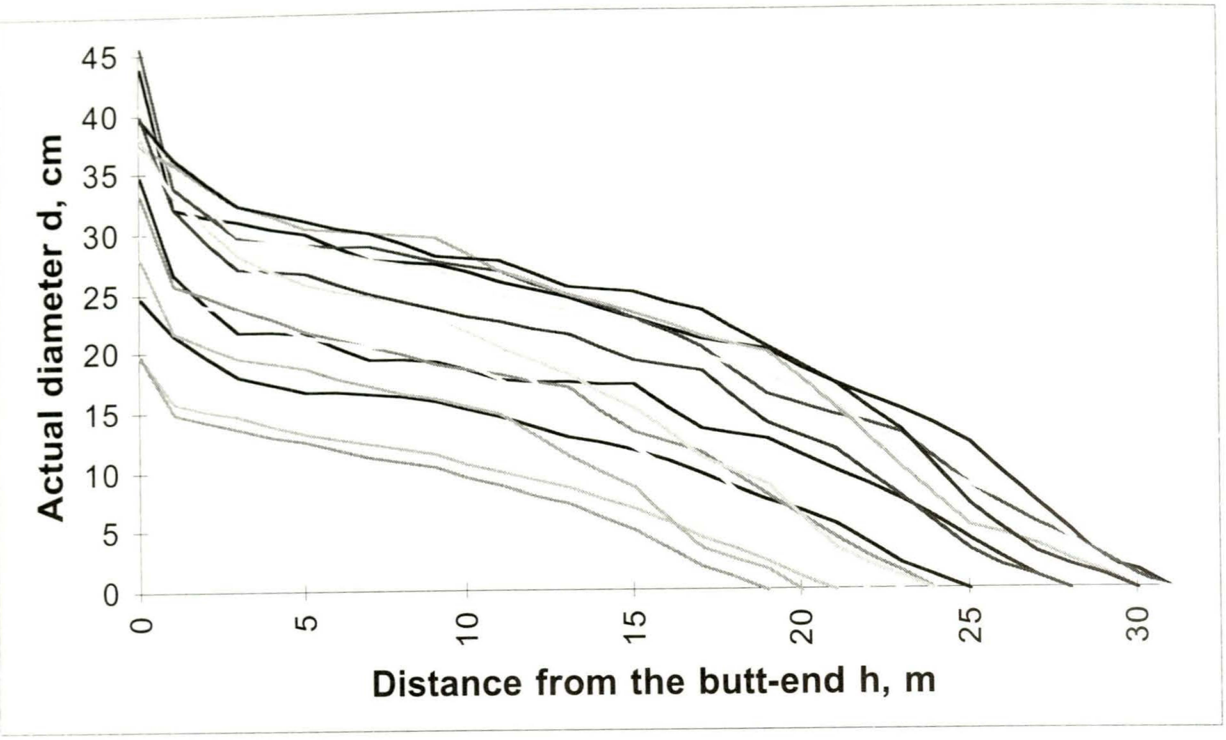


Figure 1.—*Tapering lines of 15 birch model trees before transformation.*

When looking for a solution, the recommendation was to divide the height of a tree into 20 identical parts and calculate corresponding actual diameters:

$$d_i;\quad i=0,\ 1,\ 2,..,19.$$

This was done by using hyperbolical interpolation (form. 1). The last diameter at the top of a tree is constantly equal to zero. Now it is possible to realize the linear transformation in longitudinal direction by changing the absolute height by the relative:

$$x = \frac{h}{H},\ \text{where} \qquad (2)$$

h—distance from the butt-end to a freely selected cut, m;

H—height of tree, m;

x—relative height.

In fact, the accomplished transformation in longitudinal direction is an even shortening of a trunk *H* times (fig. 2). To carry out a transformation in transverse direction or change the thickness of a trunk, the diameter in a definite relative height—for instance, 0.1—must be assumed equal to a constant value, for instance, 100:

$$\delta(x) = \frac{100 \cdot d(h)}{d(0.1H)}. \qquad (3)$$

The conventional signs used are:

d(h)—actual diameter in height *h*, cm;

d(0.1*H*)—actual diameter in height 0.1*H, cm*;

δ(*x*)—conformable relative diameter in relative height x.

Constantly $\delta_2 = \dfrac{100 \cdot d_2}{d_2} = 100$;

$$\delta_{20} = \frac{100 \cdot d_{20}}{d_2} = 0 \cdot$$

The processing of 2,794 model tree measurements resulted in the calculation of 53,000 relative diameters. Arithmetic mean values of relative diameters in connection with the relative height (table 1) are very important for further research work. Studies of the relative diameter variabilities of pine, fir, birch, aspen, and black alder disclosed an interesting detail: tapering curves of foliage trees used to have a second inflection point in the relative height of approximately 0.8. Further processing of information was considerably simplified after the transition from absolute to relative values was carried out. Now it is more convincing to indicate the type of connection being searched (fig. 3).

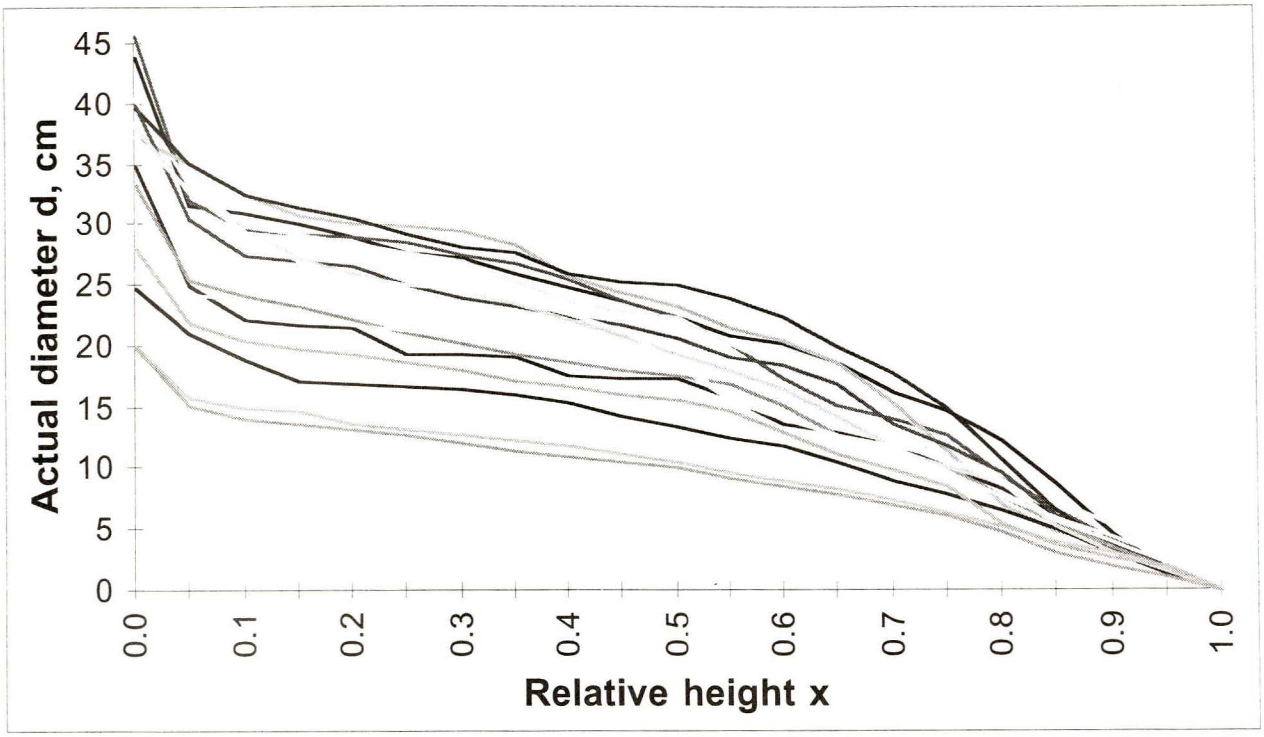


Figure 2.—*Tapering lines of 15 birch model trees after linear transformation in longitudinal direction.*

Table 1.—*Relative diameters of tree trunks*

Relative height	Pine	Fir	Birch	Aspen	Black alder
0.00	129.5	132.3	137.5	120.2	124.7
0.05	107.6	105.6	108.8	104.4	107.5
0.10	100.0	100.0	100.0	100.0	100.0
0.15	94.8	95.9	94.9	95.9	95.5
0.20	91.1	93.0	91.6	93.2	91.7
0.25	87.8	90.3	88.2	90.4	88.6
0.30	84.7	87.4	85.0	87.1	85.6
0.35	81.8	84.1	81.5	83.3	82.2
0.40	78.8	80.7	77.7	79.3	78.8
0.45	75.7	77.0	73.9	75.3	75.4
0.50	72.4	72.8	69.8	71.5	71.5
0.55	68.8	68.3	65.1	67.1	67.2
0.60	64.8	63.3	59.5	61.7	62.4
0.65	60.3	57.9	53.7	55.8	57.0
0.70	55.2	52.1	47.3	48.8	51.0
0.75	49.1	45.8	40.2	41.5	43.3
0.80	42.0	38.6	32.8	33.6	34.8
0.85	33.4	31.1	24.7	24.8	26.2
0.90	23.5	22.9	17.0	16.5	17.9
0.95	12.3	14.3	10.0	9.6	9.5
1.00	0.0	0.0	0.0	0.0	0.0

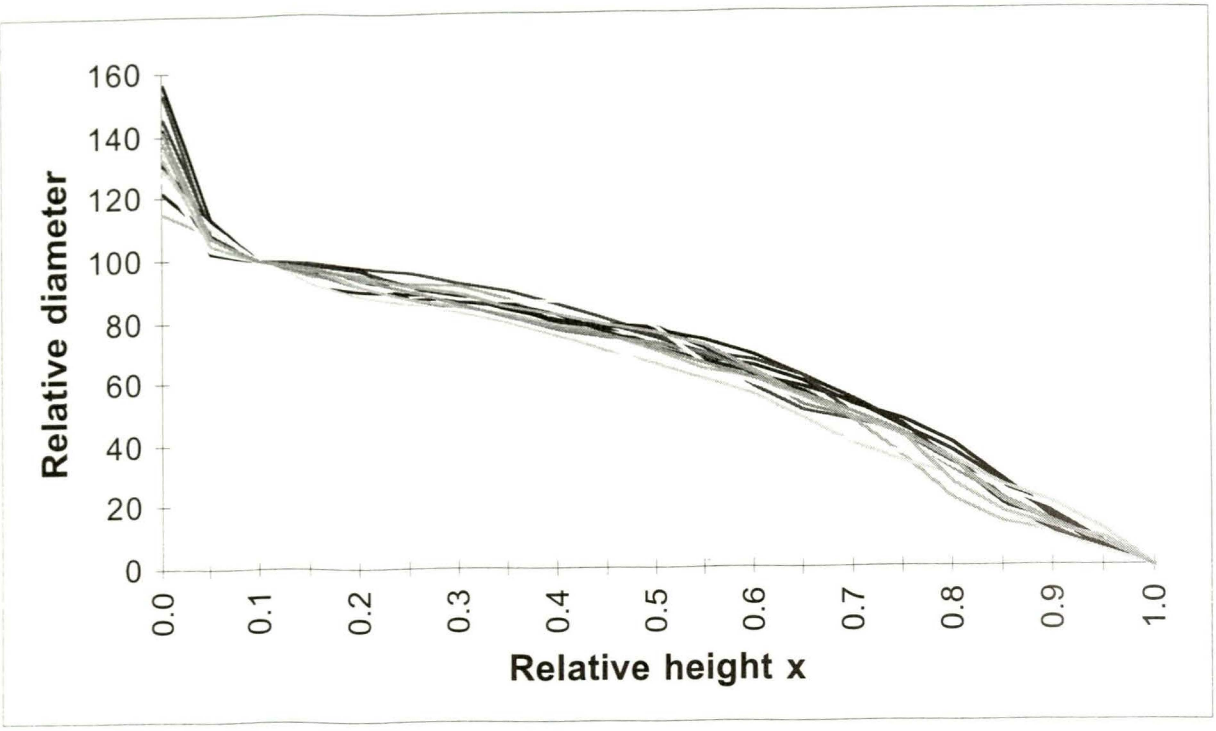


Figure 3.—*Tapering lines of 15 birch model trees after complete linear transformation in longitudinal and transverse direction.*

If the analytical expression for empirical formula is selected, a smoothing of relative diameters in dependence from the relative height (table 1) can be realized on computer by applying a standard program, for example, Microsoft Excel. Calculations have proven that the sixth power polynomial is good enough for ordinary cases. In accordance with the available information, coefficients of the sixth power polynomial

$$P_6(x) = a_0 + a_1x + a_2x^2 + \ldots + a_6x^6 \ , \qquad (4)$$

were calculated for nine tree species by using various methods in dependence of primary information (table 2). The average values of relative diameters can be approximated by empirical formula:

$$\delta = P_6(x). \qquad (5)$$

The final connection between a freely selected distance from the butt-end and the corresponding actual diameter for tree trunks with given dimensions can be obtained by applying reverse transformation, i.e., by an even extension or reduction of the mean transformed model of the tapering curve (form. 5) in longitudinal and transverse directions:

$$d = D \cdot \frac{P_6\left(\dfrac{h}{H}\right)}{P_6\left(\dfrac{1.3}{H}\right)}, \text{ where} \qquad (6)$$

D—diameter at breast height (1.3 m), cm.

The designed equation (form. 6), together with coefficients (table 2), is the mathematical model of tapering tables for tree trunks in bark. This model can be used for solving diverse tasks of forest mensuration on the computer.

Perturbation of Relative Diameters

Common features of the form of tree trunks for given species are included in the mean tapering curve equation (form. 6, table 2). An additional connection between relative diameters and dimensions of a trunk was confirmed after a more detailed investigation. It turned out that the choice of a suitable analytical expression for the approximation of the named values by using classical methods of mathematical statistics is a very complicated task. For reliable calculation results, several hundreds of model trees are needed. Because of the lack of sufficient customary measurements, an original access is necessary. Eventually, fluctuations of the form of a tree trunk are determined by biological features of species and by growing conditions. All forest forming trees have much in common. Typical features of a trunk with a given length and thickness can be obtained by changing the relative diameters within limits and specifying deviation from the average form by using indirect data such as

Table 2.—*Coefficients of the sixth power polynomial*

Tree species	a_0	a_1	a_2	a_3	a_4	a_5	a_6
Pine	118.981	-277.578	1140.525	-3037.487	4419.682	-3361.780	997.657
Fir	113.939	-203.061	827.209	-2161.251	2732.076	-1699.667	390.755
Birch	120.567	-312.074	1388.288	-3725.819	5197.005	-3788.858	1120.891
Black alder	120.224	-310.985	1450.125	-4238.703	6644.011	-5408.312	1743.640
Aspen	110.428	-143.288	530.481	-1643.304	2606.605	-2212.940	752.018
White alder	118.560	-263.482	988.135	-2376.874	3045.214	-2137.684	626.131
Oak	120.958	-354.769	2022.206	-6736.346	11231.250	-9254.632	2971.333
Ash	117.999	-282.941	1411.064	-4542.395	7964.660	-7175.007	2506.620
Lime	110.428	-143.287	530.477	-1643.287	2606.569	-2212.906	752.006

volume tables. Specification of deviation and calculation of parameters are based on their random and gradual change with succeeding computing of the volume of a tree trunk by the integration of the tapering curve equation. The final values of parameters correspond to the smallest difference between the volumetric table and the calculated results. The recommendation was to specify the deviation by using a particular coefficient called perturbation factor:

$$\gamma = 1 + \left(x^2 - 0.01\right) \cdot \left(p \cdot (H - H_0) + q \cdot (D - D_0)\right). \tag{7}$$

The conventional signs are:

D_0, H_0—dimensions of mean form trunk;
p, q—parameters of tree species.

Parameters were calculated for pine, fir, birch, black alder, aspen, white alder, oak, ash, and lime (table 3). If the perturbation factor (form. 7) is taken into account, the relative diameters are determined by formula:

$$\delta = \gamma \cdot P_6(x), \text{ or symbolically,}$$

$$\delta = F(\tfrac{h}{H}, D, H). \tag{8}$$

The equation of the trunk tapering curve becomes more complicated:

$$d = D \cdot \frac{F(\frac{h}{H}, D, H)}{F(\frac{1.3}{H}, D, H)} . \tag{9}$$

The variability of the tapering curve in connection with tree dimensions (fig. 4) is better reflected as compared to the mean values.

This perturbation method of relative diameters may seem strange. But precision is the main criterion for any method. It is not complicated to collect additional data and test recommendations. The use of a perturbation factor has allowed the design of a uniform system of standards for the assortment structure analysis in felling areas before cutting.

Variable Assortment Tables

To carry out diverse calculations of roundwood volume, a law of bark thickness distribution is needed. Analysis of model tree measurements has revealed a sufficiently exact connection between the relative thickness of bark and the relative height of the given cut. The fourth power polynomial was recommended for the approximation of the above named connection:

$$p = Q_4(x) ,$$

$$Q_4(x) = b_0 + b_1 x + b_2 x^2 + b_3 x^3 + b_4 x^4 , \tag{10}$$

Table 3.—*Parameters of perturbation factor*

Parameters	Pine	Fir	Birch	Black alder	Aspen	White alder	Oak	Ash	Lime
H_0	26	33	20	14	18	16	14	21	16
D_0	30	36	28	12	30	16	20	20	12
p	0.0070	0.0087	0.0210	0.0264	0.0074	0.0168	0.0263	-0.0021	0.0061
q	-0.0070	-0.0197	0.0000	-0.0017	0.0002	-0.0103	0.0005	0.0000	0.0000

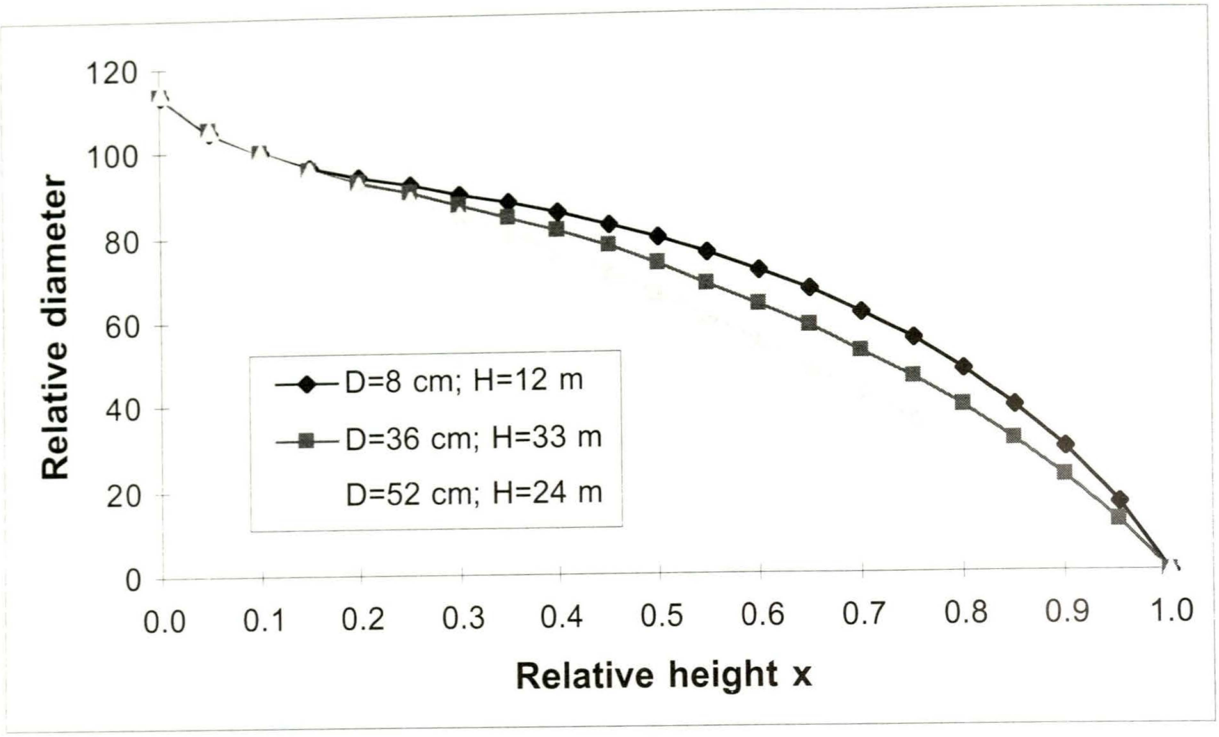


Figure 4.—*Changes of fir trunk tapering lines in dependence from tree dimensions.*

The conventional signs are:

p—double thickness of bark in percent from the diameter in bark,
x—relative height,
b_0, b_1, b_2, b_3, b_4—coefficients of the fourth power polynomial.

Coefficients were calculated for pine, fir, birch, black alder, aspen, white alder, oak, ash, and lime (table 4). Considering the equation of the tapering curve (form. 6) and the law of bark distribution (form. 10), an equation of a tapering curve for a tree trunk without bark was obtained:

$$d^* = D \cdot \frac{P_6\left(\frac{h}{H}\right)}{P_6\left(\frac{1.3}{H}\right)} \cdot \left[1 - \frac{Q_4\left(\frac{h}{H}\right)}{100}\right], \text{ where} \qquad (11)$$

d^*—diameter of the trunk without bark at a freely selected height, cm.

A more exact result is obtained if the equation with perturbation factor (form. 9) and the law of bark distribution (form. 10) are taken into consideration:

Table 4.—*Coefficients of the fourth power polynomial*

Coefficients	**Pine**	**Fir**	**Birch**	**Black alder**	**Aspen**	**White alder**	**Oak**	**Ash**	**Lime**
b_0	12.90	5.35	9.61	8.34	7.57	5.02	12.81	8.31	8.00
b_1	-55.16	-7.57	-39.92	0.93	-17.99	-10.66	-53.23	-19.75	0.89
b_2	116.32	20.37	117.49	20.45	43.35	25.69	156.65	47.60	19.61
b_3	-110.12	-13.10	-134.22	-62.45	-37.07	-21.97	-178.96	-40.70	-59.89
b_4	40.96	5.45	55.73	55.00	14.24	8.44	74.31	15.64	52.75

$$d^* = D \cdot \frac{F\left(\frac{h}{H}, D, H\right)}{F\left(\frac{1.3}{H}, D, H\right)} \cdot \left[1 - \frac{Q_4\left(\frac{h}{H}\right)}{100}\right]. \qquad (12)$$

On average, the improved tapering curve equation without bark (form. 12) conforms more closely to the form of the given tree trunk. However, calculation by that formula is more complicated.

The roundwood, the quality of which corresponds to the conditions of standards, is usually called the assortment. The volume of roundwood (or log) including bark can be calculated by the integration of the tapering curve (form. 6):

$$v = \frac{\pi}{4 \cdot 10^4} \cdot \int_{h_1}^{h_2} \left[D \cdot \frac{P_6\left(\frac{h}{H}\right)}{P_6\left(\frac{1.3}{H}\right)} \right]^2 dh \text{ , where} \qquad (13)$$

h_1, h_2—distances from the butt-end to the beginning and end of a log, m;
v—volume of log in bark, cubic meter.

For the first log, h_1=0, h_2 - length of log.

If h_1=0 and h_2=H, the volume of tree trunk V is obtained:

$$V = \frac{\pi}{4 \cdot 10^4} \cdot \int_0^H \left(D \cdot \frac{P_6\left(\frac{h}{H}\right)}{P_6\left(\frac{1.3}{H}\right)} \right)^2 dh. \qquad (14)$$

After the elementary alteration formula (form. 14) becomes more convenient for computation:

$$V = \frac{\pi \cdot D^2 \cdot H}{4 \cdot 10^4 \cdot \left[P_6\left(\frac{1.3}{H}\right) \right]^2} \cdot I_6 \text{ , where}$$

$$I_6 = \int_0^1 \left[P_6(x) \right]^2 dx \ . \qquad (15)$$

If the volume of roundwood without bark is calculated, the tapering curve equation (form. 11 or 12) can be used. If, for example, the improved equation with perturbation factor (form. 12) is chosen, then

$$v^* = \frac{\pi \cdot D^2}{4 \cdot 10^4 \cdot F^2\left(\frac{1.3}{H}, D, H\right)} \cdot \int_{h_1}^{h_2} F\left(\frac{h}{H}, D, H\right) \cdot \left(1 - Q_4\left(\tfrac{h}{H}\right) \big/ 100\right)^2 dh \text{, where} \qquad (16)$$

v*—volume of log without bark, cubic meter.

Now the required tools are ready for the generation of variable roundwood tables: the necessary equations (form. 6, 9, 11, 12) have been designed, and the uniform parameters (tables 2, 3, 4) have been calculated. Theoretically, it becomes possible to imaginarily saw the growing tree trunk in diverse versions. For each variant, a volume of roundwood, either including bark or not, can be computed. There may be some condition such as agreement with the wood processor or buyer, quality of wood, priority of fixed dimensions. The final results of the described calculations form an ordinary version of variable assortment tables. The first trials to compile variable tables were carried out at the Latvian Forest Research Institute 15 years ago.

An empirical formula has become a convenient and compact storage of information for advanced computers. After choosing an analytical expression, parameters can be obtained by mathematical simulation. For instance, the volume without bark for veneer timber sawed from the butt-end part of a birch stem can be calculated by formula:

$$\text{V} = EXP(-9.63316) \cdot L^{0.884752} \cdot R_{05}^{2.09172} \cdot T_0^{-0.0909147} \text{, where} \qquad (17)$$

L—length of veneer timber, m;
R_{05}—diameter (with bark) at 0.5 m from the butt-end in centimeters;
T_0—diameter (with bark) at the thin end of veneer timber in centimeters.

DISCUSSION

For sustainable management of forests a variety of information about the resources is needed. Some problems need further investigation. Certainly the collection of data is a very labor consuming process, but it is necessary for improving existing mathematical models or for creating a new generation of advanced models. Several directions are possible for further study. The diameter of a tree trunk at 1.3 m and its total height, in fact, are functions of time. By discovering the connection between the above named dimensions of tree and time, an impressive method for growth and yield estimation can be obtained. Mathematical models such as this one of tree trunk form may be used like basic units for designing very complicated models. The basic units can be supplemented by the distribution of trees by their dimensions as a partly random function of time. The connection between thickness and height can also be added to the basic units. Designing a mathematical model of a forest is a great problem for the 21st century.

ACKNOWLEDGMENTS

The author thanks the Latvian Forestry Research Institute SILAVA and the Latvian State Institute of Forest Inventory for their help.

The author is very grateful to the North Central Research Station of the USDA Forest Service for giving him the opportunity to take part in this conference.

The following people reviewed this manuscript: Henn Tuherm, and Imants Mangalis, Latvia University of Agriculture, Forest Faculty, Jelgava. Latvia.

Comparison of Optical Dendrometers for Prediction of Standing Tree Volume

Robert C. Parker and Thomas G. Matney

Abstract.—Enhanced sets of compatible stem profile equations were used with data collected from felled and standing pine trees to calculate tree volumes to various top merchantability limits. Standing trees were measured with the Criterion 400 Laser, Tele-Relaskop, and Wheeler Pentaprism. These measurements were used to compare accuracies of the optical dendrometers for the measurement of tree dbh and height and the prediction of tree volume from stem profile equations. The Criterion 400 Laser was more accurate for dbh and total height measurement than was the Tele-Relaskop or the Wheeler Pentaprism, but the accuracy differences are not significant in a practical sense. Mean percent differences in dbh measurement translated, in absolute units, to -0.05, +0.20, and -0.34 in. of the mean tree dbh for the Criterion 400, Tele-Relaskop, and Wheeler Pentaprism instruments, respectively. Mean percent differences in total height measurement translated, in absolute units, to 0.5, 1.6, and 1.7 ft, respectively, of the average tree height and were not practically different. The combined measurement data for dbh and dob_{16} indicated the Tele-Relaskop would produce more reliable volume results than the other instruments if the dendrometer measurements were used with form class volumes. Profile equations developed with felled-tree data produced the most consistent estimates of merchantable height and cubic foot volume to specified merchantable top limits. In general, the Criterion 400 produced the smallest mean differences in standing tree measurements and profile equation predictions of merchantable height and cubic foot volume. However, the Tele-Relaskop produced the most consistent tree measurement and profile prediction trends. The Wheeler Pentaprism was the least accurate of the three dendrometers.

The prediction of standing tree volume has traditionally involved destructive measurement methods, but these methods cannot be used in fragile forest ecosystems. Recent developments in telescopic and laser dendrometer instruments make it feasible to obtain upper stem measurements of standing trees in a non-destructive manner. However, the measurement accuracy and application technology of these instruments have not been evaluated. Bruce (1975) discussed some of the steps and limitations in evaluating accuracy of tree measurements made with optical instruments and emphasized that "... an adequate evaluation of their accuracy and that of less expensive devices is needed."

The Tele-Relaskop (Bitterlich 1978) is a precision, telescopic dendrometer that has been used, in limited industrial and research applications, to develop taper and volume functions for standing trees (Bitterlich 1984; Heske and Parker 1983; Parker 1983, 1997). Parker (1983, 1997) expanded the theoretical conoid concepts for tree volume computations proposed by Bitterlich with polynomial taper functions, developed application software for the microcomputer, and compared volume and taper applications with conventional inventory procedures. Although Bitterlich (1984) stated the relative accuracy of the Tele-Relaskop as "percentage readings of tree diameters at an accuracy to the nearest 1/100 of 1 percent whilst readings for vertical dimensions only allow estimates to the nearest 1/10 of 1 percent," its accuracy for tree measurement and volume computation has not been established with documented research.

Laser dendrometers and distance measuring instruments are being developed, and some have been tested by the USDA Forest Service (Jasumback and Carr 1991). According to Carr (1992), laser technology of the Criterion model 400, manufactured by Laser Technology, Inc. (1991, 1992), has advanced to a point where accurate short- and long-range measurements are possible on non-reflective objects such as trees. In forestry applications, the Criterion 400 has been used for measuring tree heights and diameters, locating a specific height or diameter, selecting sample trees in variable plot inventories, measuring horizontal and slope distances, and determining coordinate azimuths and distances to defined targets (LaBau 1991, Liu *et al.* 1995). In engineering and

---

Associate Professor and Professor of Forest Biometrics, respectively, Department of Forestry, College of Forest Resources, Mississippi State University, Mississippi State, MS 39762, USA.

mapping applications, the Criterion 400 has been evaluated by Moll (1992), Uren and Garner (1994), Byrnes *et al.* (1994), Pepling (1995), and Liu (1995). Although the accuracy of the Criterion 400 has been widely evaluated for surveying and engineering applications, there is little documented research pertaining to its accuracy in measurement of tree dimensions and no research on its accuracy for upper stem measurement and/or volume determination of standing trees.

The Wheeler Pentaprism (Wheeler 1962) has been used in forestry applications for obtaining upper stem diameters for many years. Although it does not have the telescopic optics of the Tele-Relaskop or sophisticated electronic circuitry of the Criterion 400, it can provide consistent estimates of upper stem diameters at heights determined by an attached clinometer.

Stem profile equations provide the most flexible methods of calculating tree volumes to specified merchantable top diameters from standing tree measurements. The technology of stem profile systems used by Burkhart (1977), Clutter (1980), Matney and Sullivan (1980 and 1982), and Van Deusen *et al.* (1982) did not allow the use of upper stem diameters. Newer technology has produced compatible sets of stem profile equations (Matney and Parker 1992) that allow the prediction of tree volume to user-defined top merchantability limits.

This paper compares dbh and height measurements taken on standing trees with the Criterion 400 Laser, Tele-Relaskop, and Wheeler Pentaprism with direct measurements after felling. It also compares predicted volumes and heights from an enhanced set of compatible stem profile equations using the optical measurements on standing trees and the direct measurements on felled trees.

DATA COLLECTION

One hundred sample trees (*Pinus taeda* L.) were selected from a stand on the John Starr Memorial Forest that had been previously thinned from below to remove intermediate and suppressed trees. The sample trees ranged from 5.7 to 24.2 in. in dbh and from 53 to 109 ft in height (fig. 1). On each sample tree, breast height (4.5 ft above average ground level) and the top of the first 16.0-ft log

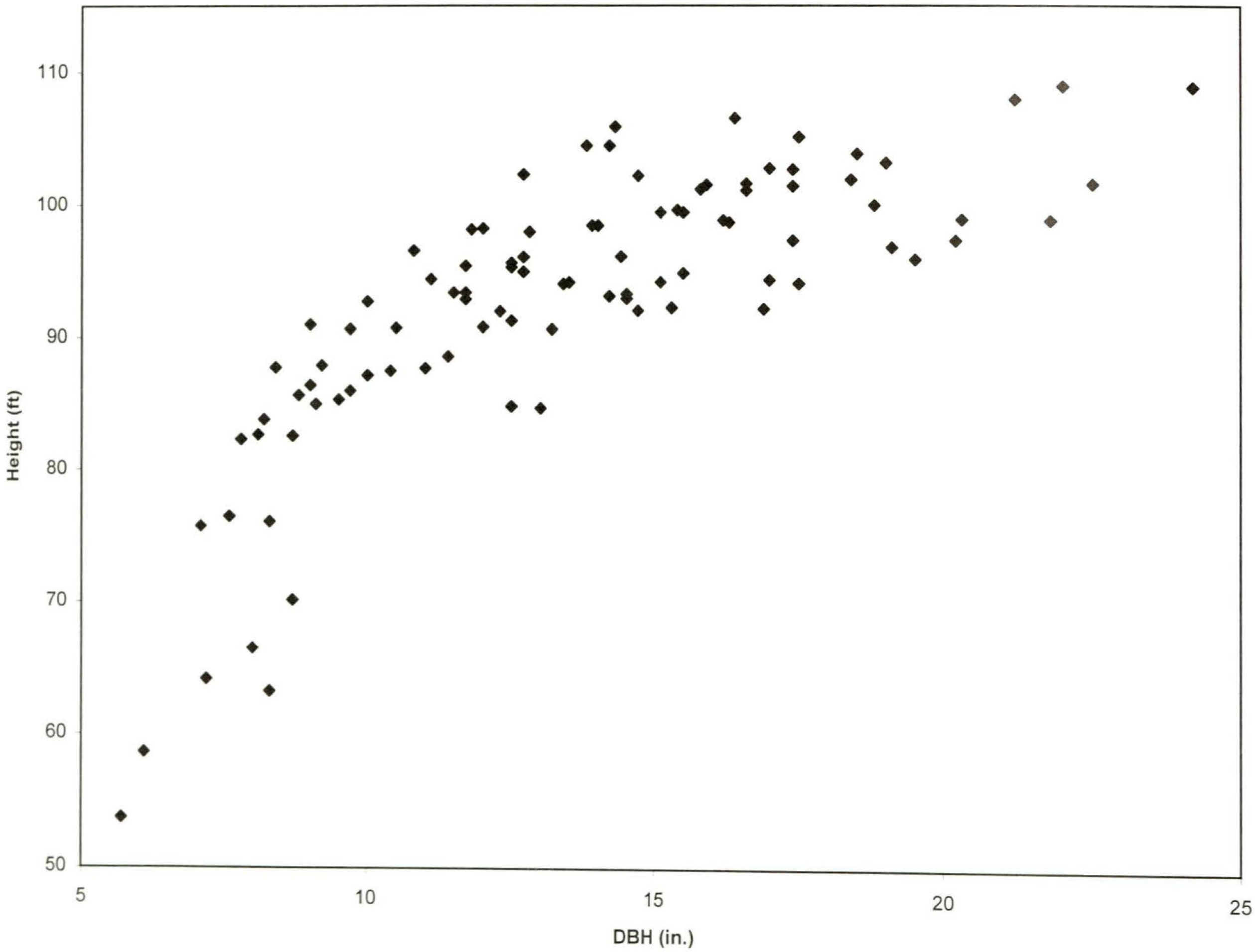


Figure 1.—*Dbh and total height distribution of 96 sample loblolly pine trees measured with Criterion 400 Laser, Tele-Relaskop, and Wheeler Pentaprism dendrometers and felled for prediction of standing tree volumes. Dbh was measured with a caliper and height with a tape after felling.*

(16.5 ft, assuming a 0.5-ft stump) were marked with a horizontal orange line and measured with a caliper.

Since operational inventories in fragile ecosystems would preclude the use of destructive measurement of felled-trees (at 4.0-ft intervals) and would possibly be limited by time and/or economics, stem measurement data obtained with optical or laser dendrometers would most likely be taken at stem intervals exceeding 4.0 ft. Therefore, dendrometer measurements of stem diameter (outside bark) and height were taken at breast height, at the top of the first 16.0-ft log, at two intermediate points spaced approximately equal between the top of the first 16.0-ft log and an estimated 3.0-inch top (ob), at an estimated 3.0-inch top (ob), and at total tree height. These stem measurement locations correspond to the dbh, four intermediate, and total height points described by Parker (1997) in previous applications of the Tele-Relaskop. Due to time and cost limitations, one member of the sample crew took all measurements with a specific instrument. The three resulting databases represent three different observers. Therefore, observer accuracy is confounded with instrument accuracy in a statistical sense. Observer effects were minimized, however, by a 2-day training period after which the author assigned each instrument to the observer who demonstrated the best proficiency and accuracy with the instrument. The author and two of four field technicians took all measurements, and each observer was deemed equal in the use of each instrument.

Sample trees were felled with a 0.5-ft stump. Diameters (ob) and bark thickness measurements were taken at the stump, 3.0 ft (2.5 ft above stump height), breast height (4.0 ft above stump height), and 4.0-ft intervals along the stem to the terminal bud. Diameters were measured to the nearest 0.1 in. with a steel caliper, and two bark thicknesses were obtained (one under each caliper arm) with a bark gauge to the nearest 0.1 in. Total tree height was computed as the sum of the measurement intervals and the distance from the last diameter measurement to the tip.

DATA ANALYSIS

Although the primary objective of this study was to compare volume prediction accuracy of stem profile equations developed from optical dendrometer and felled-tree data, estimates of "point" measurement accuracy could be obtained for common measurements taken at breast height, 16.5 ft, and total height. The data sets were reduced to 96 trees because 4 trees in the felled-tree data set had at least one missing (inaccessible) measurement at or below breast height caused during the felling operation. Mean percent difference and standard error of the mean percent difference between the dendrometer measurements and felled-tree values were computed (table 1). The observed differences between felled-tree values and dendrometer measurements are expressed as a percentage of felled-tree value. Felled tree diameters at breast height and 16.5 ft were measured with a caliper in the same plane as viewed with the optical dendrometers.

During operational forest inventories, the measurements most commonly taken are dbh and merchantable height to a variable top diameter (ob) and/or total tree height. To simulate these measurement practices and to obtain sample tree volumes to variable top diameters, a compatible set of stem profile equations was developed to allow the prediction of outside- and inside-bark stem diameters at desired merchantability points from standing tree measurements of dbh and total tree height. The profile prediction system models used in this study are enhanced versions of the non-segmented, third-degree polynomial conditioned through the top (i.e., at $h_i=h_{total}$ or $X=h_i/h_{total}=1$, $dob_{hi}=0$) used by Parker (1983, 1997) and the

Table 1.—*Comparisons of optical dendrometers for diameter and height measurement of standing loblolly pine trees where* ***d*** *is mean percent difference (observed difference as a percent of felled-tree value) and sd is the standard error of the mean percent difference (Basis: 96 trees)*

Measurement	Statistic	Criterion 400	Tele-Relaskop	Wheeler Pentaprism
			Percent	
DBH	$\bar{d}$	-0.39	+1.41	-2.40
($\overline{dbh}$ =14.1 in.)[1]	$s_{\bar{d}}$	+0.53	+0.40	+0.57
DOB_{16}	$\bar{d}$	-1.92	+1.54	-4.16
($\overline{dob}_{16}$ =12.6 in.)[1]	$s_{\bar{d}}$	+0.60	+0.66	+0.56
Total Height	$\bar{d}$	+0.59	+1.68	+1.87
($\overline{H}_t$=92.8 ft)[1]	$s_{\bar{d}}$	+0.45	+0.78	+0.3

[1] Diameter measured with a caliper and total height with a tape after felling.

fifth-order polynomial constrained through dbh and the top merchantability limit (i.e., $dob_{hi}/dbh=1$ when $h_i=4.5$ ft and dob_{h_i} = merchantable top dob when $h_i=h_m$) used by Matney and Parker (1992).

The set of profile prediction system models applied to the felled and optical dendrometer tree data where b_i and b'_i are regression coefficients for outside and inside bark, respectively, are:

At stump height of 0.5 feet (i.e. $h_i = 0.5$ ft)

$$\frac{dob_{0.5}}{dbh_{ob}} = b_1\left(\frac{1}{dbh_{ob}}\right) + b_2$$

(1)

$$\frac{dib_{0.5}}{dbh_{ob}} = b'_1\left(\frac{1}{dbh_{ob}}\right) + b'_2$$

At dbh: dbh_{ob} to dbh_{ib} conversions (i.e. $h_i = 4.5$ ft)

$$\frac{dbh_{ib}}{dbh_{ob}} = b_3\left(\frac{1}{dbh_{ob}}\right) + b_4 \tag{2}$$

Below breast height (i.e. $h_i < 4.5$ ft)

$$\begin{aligned} y_i &= 1 + b_5\left(x_i - w_i\right) + b_6\left(x_i^2 - w_i^2\right) \\ z_i &= 1 + b'_5\left(x_i - w_i\right) + b'_6\left(x_i^2 - w_i^2\right) \end{aligned} \tag{3}$$

where:

$$y_i = \frac{dob_{h_i}}{dbh_{ob}} \qquad z_i = \frac{dib_{h_i}}{dbh_{ob}}$$

$$x_i = \frac{h_i}{h_t} \qquad w_i = \frac{4.5}{h_t}$$

Above breast height (i.e., $h_i > 4.5$ ft)

$$\begin{aligned} y_i &= \frac{x_i - 1}{w_i - 1} + b_7\left[\left(x_i^2 - 1\right) - \frac{\left(w_i^2 - 1\right)\left(x_i - 1\right)}{\left(w_i - 1\right)}\right] + b_8\left[\left(x_i^3 - 1\right) - \frac{\left(w_i^3 - 1\right)\left(x_i - 1\right)}{\left(w_i - 1\right)}\right] \\ z_i &= \frac{x_i - 1}{w_i - 1} + b'_7\left[\left(x_i^2 - 1\right) - \frac{\left(w_i^2 - 1\right)\left(x_i - 1\right)}{\left(w_i - 1\right)}\right] + b'_8\left[\left(x_i^3 - 1\right) - \frac{\left(w_i^3 - 1\right)\left(x_i - 1\right)}{\left(w_i - 1\right)}\right] \end{aligned} \tag{4}$$

Bark relationship above breast height (i.e., $h_i > 4.5$ ft)

$$\left(\frac{dib_{h_i}}{dob_{h_i}}\right) = \left(\frac{dbh_{ib}}{dbh_{ob}}\right) e^{b'_9\left[\frac{dbh_{ob}}{dob_{h_i}} - 1\right]^{0.25}} \tag{5}$$

Equation (1) predicts stump diameter (ob and ib) at 0.5 ft aboveground from dbh_{ob}. Equation (2) predicts dbh_{ib} from dbh_{ob}. Equation (3) is a constrained, second-degree polynomial, profile model to predict stem diameter (ob and ib) between stump height and breast height. Equation (3) is constrained through breast height so that at h_i=4.5 ft, dob_{hi}/dbh_{ob} =1. Equation (4) is a constrained, third-degree polynomial, profile model to predict stem diameter (ob and ib) between breast height and total tree height. Equation (4) is constrained through both breast and total height so that at $h_i=h_{total}$, dob_{h_i} =0 and dib_{h_i} =0. Thus, Equation (4) is constrained through ratio estimate points 1 and 0. Equation (5) predicts the dib/dob (i.e., bark) relationship along the upper stem above breast height. The exponent in Equation (5) was fixed at 0.25 because attempts to fit that parameter often cause convergence problems with some nonlinear procedures. Equation (5) was developed from the felled-tree data for use with the dendrometer data sets when an inside bark diameter is needed. Computing the bark relationship with Equation (5) is more efficient than computing the ob and ib values in two steps with Equation (4).

PROFILE EQUATION RESULTS

The resulting profile equations to predict diameters below breast height and the bark relationship above breast height for the felled tree data set, where $s_{y.x}$ is the standard error of prediction and I^2 is the index of fit for 96 trees, are:

At stump height of 0.5 feet (i.e., h_i = 0.5 ft)

$$\frac{dob_{0.5}}{dbh_{ob}} = 0.9364\left(\frac{1}{dbh_{ob}}\right) + 1.1294 \qquad \text{with n=96, } s_{y.x=0.0708} \text{ and } I^2 = 0.1165 \qquad (6)$$

$$\frac{dib_{0.5}}{dbh_{ob}} = -0.0149\left(\frac{1}{dbh_{ob}}\right) + 1.0342 \qquad \text{with n=96, } s_{y.x=0.0697} \text{ and } I^2 = 0.0000$$

At dbh: dbh_{ob} to dbh_{ib} conversions (i.e., h_i = 4.5 ft)

$$\frac{dbh_{ib}}{dbh_{ob}} = -0.3815\left(\frac{1}{dbh_{ob}}\right) + 0.8896 \qquad \text{with n=96, } s_{y.x=0.0295} \text{ and } I^2 = 0.1124 \qquad (7)$$

Below breast height (i.e., h_i < 4.5 ft)

$$y_i = 1 + -7.1727(x_i - w_i) + 45.3420(x_i^2 - w_i^2) \qquad \text{with n=192, } s_{y.x=0.0567} \text{ and } I^2 = 0.6691 \qquad (8)$$

$$z_i = 1 + -8.0688(x_i - w_i) + 62.1590(x_i^2 - w_i^2) \qquad \text{with n=192, } s_{y.x=0.0572} \text{ and } I^2 = 0.6778$$

where: $y_i = \frac{dob_{h_i}}{dbh_{ob}}$ $\quad z_i = \frac{dib_{h_i}}{dbh_{ib}}$

$x_i = \frac{h_i}{h_t}$ $\quad w_i = \frac{4.5}{h_t}$

Bark relationship above breast height (i.e., h_i > 4.5 ft)

$$\left(\frac{dib_{h_i}}{dob_{h_i}}\right) = \left(\frac{dbh_{ib}}{dbh_{ob}}\right) e^{0.0642\left[\frac{dbh_{ob}}{dob_{h_i}} - 1\right]^{0.25}} \qquad \text{with n=1,600, } s_{y.x=0.0368} \text{ and } I^2 = -0.5791 \qquad (9)$$

The parameter estimates and statistics of fit for Equation (4) developed from the felled-tree and dendrometer data taken above breast height, are shown in table 2. Optical and laser dendrometers are most commonly used to obtain outside bark diameters for above-breast height stem locations because of stump visibility limitations, so only the coefficients for Equation (4) were obtained for the dendrometers.

Table 3 shows the statistical significance of the profile system equation for outside bark prediction above breast height (Equation 4) for the felled tree, Criterion 400, Tele-Relskop, and Wheeler Pentaprism data sets. The regression coefficients of each data set equation were judged significantly different from zero, and each data set equation was judged significantly different from other equations at the 0.01 level.

Profile equations were fitted to the felled tree data set and to the three sets of optical dendrometer data. Heights to various diameters and cubic foot volumes were predicted with the profile equations and compared to the computed, felled-tree volumes. Table 4 shows the mean percent differences between heights and volumes computed with the profile system equations and measured felled-tree values. Cubic foot volumes and merchantable heights of the felled trees were computed to 0, 3, 6, 8, and 10 inch top diameters (ob) using Smalian's formula and linear interpolation of intermediate bolt diameters. Percent difference is the arithmetic difference between the computed value from the profile system equation(s) and the measured felled-tree value expressed as a percentage of felled-tree value. Equation (4) coefficients for each of the felled-tree and dendrometer data sets (table 2) were used to compute upper stem diameters at 4.0-ft intervals above breast height. Diameters below breast height (0.5 and 3.0 ft) were computed for all data sets with felled-tree Equations (6) and (8). Bolt length to a specified top merchantability limit that was contained within a bolt was obtained by linear interpolation of computed endpoint bolt diameters.

Table 2.—*Tree profile prediction system parameter estimates* and statistics of fit for felled-tree and optical dendrometer (above-breast height) data for loblolly pine where ob and ib are outside and inside bark, n is number of observations, $s_{y.x}$ is the standard error of prediction, and I^2 is the index of fit*

	Felled-tree		**Criterion 400**	**Tele-Relaskop**	**Wheeler Pentaprism**
Parameter	**ob**	**ib**	**ob**	**ob**	**ob**
b_7	1.74963	1.1616	1.8016	1.6914	1.9809
b_8	-1.5837	-1.3391	-1.5607	-1.5266	-1.6567
n	1,699	1,699	477	476	470
$s_{y.x}$	0.0457	0.0484	0.0642	0.0623	0.0508
I^2	0.9665	0.9651	0.9589	0.9624	0.9737

* for above-breast height tree profile equations:

$$y_i = \frac{x_i - 1}{w_i - 1} + b_7\left[(x_i^2 - 1) - \frac{(w_i^2 - 1)(x_i - 1)}{(w_i - 1)}\right] + b_8\left[(x_i^3 - 1) - \frac{(w_i^3 - 1)(x_i - 1)}{(w_i - 1)}\right]$$

$$z_i = \frac{x_i - 1}{w_i - 1} + b_7'\left[(x_i^2 - 1) - \frac{(w_i^2 - 1)(x_i - 1)}{(w_i - 1)}\right] + b_8'\left[(x_i^3 - 1) - \frac{(w_i^3 - 1)(x_i - 1)}{(w_i - 1)}\right]$$

where:

$$y_i = \frac{dob_{h_i}}{dbh_{ob}} \qquad z_i = \frac{dib_{h_i}}{dbh_{ob}}$$

$$x_i = \frac{h_i}{h_t} \qquad w_i = \frac{4.5}{h_t}$$

Table 3.—*Statistical significance of the profile prediction system equation*[1] *for outside bark measurements above-breast height for the felled-tree and optical dendometer databases (Basis: 96 loblolly pine trees)*

Data Set	SS_e	df	F_{calc}[2]	Prob
1Felled-tree	3.54293	1,696	7076.36	<0.0001
2Criterion 400 Laser	1.95140	474	715.54	<0.0001
3Tele-Relaskop	1.83615	473	830.47	<0.0001
4Wheeler Pentaprism	1.20306	467	1016.60	<0.0001
Pooled1234	8.71041	3,116	1.0188	<0.0001
Pooled12	5.56685	2,172	1.0123	<0.0001
Pooled13	5.38912	2,171	1.0009	<0.0001
Pooled14	4.87935	2,165	1.0272	<0.0001
Pooled23	3.80673	949	1.0030	<0.0001
Pooled24	3.16119	943	1.3068	<0.0001
Pooled34	3.08766	942	1.0138	<0.0001

[1]
$$y_i = \frac{x_i - 1}{w_i - 1} + b_7\left[\left(x_i^2 - 1\right) - \frac{\left(w_i^2 - 1\right)\left(x_i - 1\right)}{\left(w_i - 1\right)}\right] + b_8\left[\left(x_i^3 - 1\right) - \frac{\left(w_i^3 - 1\right)\left(x_i - 1\right)}{\left(w_i - 1\right)}\right]$$

where:

$$y_i = \frac{dob_{h_i}}{dbh_{ob}} \qquad x_i = \frac{h_i}{h_t} \qquad w_i = \frac{4.5}{h_t}$$

[2]
$$F_{\sum n_i - p, \sum (n_i - p)} = \left[\frac{PooledSS_e}{\sum n_i - p}\right] \div \left[\frac{\sum SS_{e_i}}{\sum (n_i - p)}\right]$$

Table 4.—*Mean percent differences (difference between felled-tree measurement and profile equation prediction as percent of felled-tree value -* $\bar{d}$*) and standard error of the mean percent difference (*$s_{\bar{d}}$*) for profile equation predictions of tree height and cubic foot volume from felled-tree and optical dendrometer data (Basis: 96 loblolly trees)*

Profile value (mean of actual value)	Felled-tree		Criterion 400		Tele-Relaskop		Wheeler Pentaprism	
	$\bar{d}$	$s_{\bar{d}}$	$\bar{d}$	$s_{\bar{d}}$	$\bar{d}$	$s_{\bar{d}}$	$\bar{d}$	$s_{\bar{d}}$
Height to 0 in. top (92.3 ft)	-0.002	0.002	+0.583	0.456	+1.684	0.781	+1.874	0.330
Height to 3 in. top (80.4 ft)	+1.873	0.355	+1.695	0.589	+3.401	0.794	+2.484	0.476
Height to 6 in. top (64.7 ft)	+3.400	1.410	-0.385	1.744	+5.318	1.463	-3.606	1.725
Height to 8 in. top (49.6 ft)	+4.805	1.800	+2.031	3.678	+9.439	2.158	-4.999	2.804
Height to 10 in. top (34.5 ft)	+6.212	2.848	-0.039	3.036	+11.236	3.025	-4.735	3.209
Volume to 0 in. top (49.4 ft^3)	+0.483	0.938	-3.027	1.305	+3.658	1.278	-7.031	1.252
Volume to 3 in. top (49.2 ft^3)	+0.496	0.966	-3.117	1.323	+3.663	1.295	-7.226	1.273
Volume to 6 in. top (47.3 ft^3)	+1.891	1.552	-3.594	2.101	+5.635	1.699	-10.379	1.956
Volume to 8 in. top (43.1 ft^3)	+2.315	1.734	-1.089	3.817	+8.728	2.211	-10.549	2.878
Volume to 10 in. top (36.4 ft^3)	+3.277	2.631	-3.217	3.225	+10.085	3.112	-9.782	3.249

DENDROMETER COMPARISONS

Point Estimates

The Criterion 400 was more accurate for dbh and total height measurement than the Tele-Relaskop or the Wheeler Pentaprism (table 1). Although the mean percent differences were significantly different statistically, they were most likely not different in a practical sense. The mean percent differences translated in absolute units to -0.05, +0.20, and -0.34 in. of the mean tree dbh for the Criterion 400, Tele-Relaskop, and Wheeler Pentaprism instruments, respectively. None of these mean differences would result in a change in tree diameter for a 1-in. dbh class interval.

The mean percent differences for a quadratic mean dob$_{16}$ of 12.6 in. would translate, in absolute units, to -0.24, +0.19, and -0.52 in. for the Criterion 400, Tele-Relaskop, and Wheeler Pentaprism, respectively. Although these differences might appear to be insignificant from a practical standpoint, they could translate into significant volume differences if the dbh and dob$_{16}$ dendrometer measurements were used to obtain Mesavage and Girard form class volumes (Mesavage,and Girard 1946, Parker 1998). For example, using the average tree values of dob$_{16}$ = 12.6 in. and dbh$_{ob}$ = 14.1 in., Equation (7) for dbh$_{ib}$, and Equation (9) for dib$_{16}$, the computed form class for the "average tree" would be:

$$\begin{aligned} dbh_{ib} &= -0.3815 + 0.8896(14.1 \text{ in. } dbh_{ob}) \\ &= 12.16 \text{ in.} \qquad \text{from Equation (7)} \end{aligned}$$

$$\begin{aligned} dib_{16} &= 12.6(12.16/14.10)\exp[0.0642(14.1/12.6 - 1)^{0.25}] \\ &= 11.29 \text{ in.} \qquad \text{from Equation (9)} \end{aligned}$$

$$\begin{aligned} FC &= (11.29/14.10)100 \text{ percent} \qquad \text{from definition of} \\ &= 80.04 \text{ percent} = 80 \text{ percent} \qquad \text{form class} \end{aligned}$$

Likewise, using the resulting average dob$_{16}$ values for the dendrometers (i.e., 12.6-0.24, 12.6+0.19, 12.6-0.52), the resulting dbh$_{ob}$ values (i.e., 14.1-0.05, 14.1+0.20, 14.1-0.34), Equation (7) for dbh$_{ib}$, and Equation (9) for dib$_{16}$, the computed form classes for the "average" Criterion 400, Tele-Relskop, and Wheeler Pentaprism tree would be 79 percent, 80 percent, and 79 percent, respectively. If the assumption of 3 percent (bd ft) volume change per form class point is used, the volume differences would be -3 percent, 0 percent, and -3 percent, respectively. Cubic foot volume changes approximately 2 percent per form class point. Thus, the combined measurement data for dbh and dob$_{16}$ indicate that the Tele-Relaskop would produce more reliable volume results than would the other instruments if the dendrometer measurements were used with form class volumes.

The results in table 1 indicate that the Criterion 400 was more accurate (in a practical sense, or showed less bias in a statistical sense) for total height measurement than was the Tele-Relaskop or the Wheeler Pentaprism. Again, the mean percent differences are not different from a practical standpoint because they translate to absolute height differences of 0.5, 1.6, and 1.7 ft from the average tree height of 92.8 ft. The height differences associated with the Wheeler Pentaprism are attributable to the accuracy of the attached clinometer, not the optics of the dendrometer.

Profile Equation Estimates

All upper stem profile equations (from Equation (4)) were judged to be statistically significant, and all possible pairwise comparisons showed that each equation was significantly different from the others at a significance probability of less than 0.0001 (table 3). The large degrees of freedom in the pooled comparisons forced all comparisons to be judged significantly different.

Because the primary objective of this study was to compare volume prediction accuracy of stem profile equations developed from optical dendrometer and felled-tree data, estimates of merchantable height (i.e., stem length) and cubic foot volume to various top merchantability limits were computed with the profile equations for each data set and compared to the felled-tree values (table 4). The ob upper stem profile equation coefficients for each data set (b_7 and b_8 in table 2) were used to compute estimates of merchantable height and volume above breast height. Cubic foot volume below breast height was computed for all data sets with predicted diameters at 0.5 and 3.0 ft from felled-tree Equations (6) and (8), respectively. Profile equations for predicting diameters below breast height were not developed for the dendrometers because in field applications, visibility of the stump and most stem locations below breast height is severely limited by forest vegetation. This is not a serious limiting factor in dendrometer use because the stem section below breast height can be treated as a cylinder or other appropriate geometric solid.

The accuracy of computed height (stem length) and volume values to a specified merchantability limit from a felled-tree profile equation diminishes as the merchantability limit moves down the stem from the top toward breast height (table 4). This decline in prediction accuracy is attributable in part to changes in taper caused by inflection points of the stem profile. The upper stem profile equations used in this study are constrained through the top and breast height, but as the rate of stem taper decreases in the mid-portion of the tree bole above breast height, relatively small changes in predicted diameter result in large changes in stem length (height). For example, the mean measured felled-tree heights in table 4 reflect a taper rate of 0.252 in./ft between the tree top and a 3-in. top dob, 0.191 in./ft between 3 in. and 6 in., 0.132 in./ft between 6 in. and 8 in., 0.132 in./ft between 8 in. and 10 in., and 0.134 in./ft between 10 in. and the average dbh of 14.1 in. These "average tree" taper rates show that the stem profile is "relatively flat" (actually, the taper rate is relatively constant) between a 6-in. top and dbh. Thus, a +4.8 percent error in height to an 8-in. top translates to +2.4 ft, which equates to a error of +0.295 in. in diameter prediction if the taper rate is 0.132 in./ft. From a practical standpoint, a 4-6 percent error in merchantable height prediction in the mid-bole region of a standing tree should have little impact on volume prediction.

The error associated with profile equation prediction of merchantable height (table 4) increases in a consistent manner as the top merchantability limit increases (i.e., moves down the stem toward dbh) for the felled-tree and Tele-Relaskop data sets, appears to be random for the Criterion 400 data, and has a segmented trend for the Wheeler data.

Errors in profile prediction of cubic foot volume should be attributable to the combined effects of errors in merchantable height and stem diameter prediction. For example in table 4, the average height prediction error (expressed as mean percent difference) for the felled-tree data profile equation is +4.805 percent or 2.38 ft for the 8-in. top. Using the previously established taper rate of 0.132 in./ft, the end diameter of this +2.38 ft "error bolt" would be approximately 8.3 in. and its cubic foot volume would be approximately +0.86 ft^3. The actual volume difference for the 8-in. top in table 4 is +2.315 percent or 0.99 ft^3.

Overestimation of height and/or stem diameter should result in overestimation of cubic foot volume. The computed values for felled-tree and Tele-Relaskop equations produced consistent error patterns in diameter, height, and cubic foot volume. The Tele-Relaskop overestimated dbh, dob$_{16}$, and total tree height (table 1), and the resulting profile equations overestimated merchantable height and therefore cubic foot volume (table 4). The Criterion 400 underestimated standing tree diameters, overestimated total height, and had both positive and negative estimation errors in profile height prediction. Yet, the profile equation volume prediction was consistently low. Because cubic foot volume varies with the square of bolt diameter, it must be concluded that the Criterion 400's underestimation of stem diameter has a stronger influence on volume prediction than does its inconsistent estimation of height. Likewise, the Wheeler Pentaprism underestimated standing tree diameters and the resulting profile equations consistently underestimated cubic volume by 7.0 to 10.5 percent.

It is obvious that profile equations developed with felled-tree data produce the most consistent estimates of merchantable height and cubic foot volume to various merchantable top limits. It is difficult, however, to make definitive conclusions about the accuracy ranking of the Criterion 400, Tele-Relaskop, and Wheeler Pentaprism. In general, the Criterion 400 produced the smallest mean differences in standing tree measurements and profile equation predictions of merchantable height and cubic foot volume. On the other hand, the Tele-Relaskop produced the most consistent tree measurement and profile prediction trends. There is no doubt that the Wheeler Pentaprism was the least accurate of the three dendrometers in a statistical sense, but these inaccuracies may not be relevant in a practical sense.

LIMITATIONS AND RECOMMENDATIONS

The results of this study indicate that the Criterion 400 is slightly more accurate for measurement of tree diameters and heights than the Tele-Relaskop. It is approximately 50 percent more costly than the Tele-Relaskop and has both advantages and limitations for forestry applications. The primary advantage of the Criterion 400 is its surveying and distance measuring capabilities. Its most serious limitations include laser deflection on brush and tree foliage between the instrument and the target stem location, and poor light quality and graduation intervals on the scope recticle for diameter measurement. Laser deflection becomes extremely critical when measuring stem diameter because diameter is directly proportional to the true horizontal distance to the target tree and inversely proportional to the product of the graduation interval on the scope reticle and the cosine of the vertical angle to the stem measurement point. An erroneous target distance and/or resultant diameter reading are the only clues to indicate deflection and the user must judge the relevance of the acquired measures. This limitation can be overcome with a target reflector and an electronic filter to discriminate between light reflected from the target reflector and vegetation (Carr 1996).

The graduation intervals on the scope recticle are difficult to see against some background conditions and difficult to read because of the uniform black graduations. The user must be continually aware of the resulting diameter and height measure so that another measurement can be taken if the measure(s) seem out of range. Tree diameters would be much easier to measure if the scope recticle graduations had contrasting tic marks: some oriented up and some oriented down from the primary horizontal line. A variable power scope would also improve the visual capabilities.

The Tele-Relaskop has relatively good internal light qualities, and its 8X magnification allows the user to see the tree stem against various background lighting conditions. The alternating black and white horizontal graduations are easy to see, but the user must be extremely careful in aligning the left side of a white-black graduation unit (1 percent) on the outer edge of the stem and reading the "vernier" on the right side to the nearest 0.01 percentage unit (Parker 1997). The vertical scale must be read to the nearest 1/4 to 1/2 percentage unit for upper stem measurements. Because stem diameter and height measurements are obtained in relative percentage units of the horizontal instrument distance from the tree and the horizontal distance is determined from measured dbh, measurement of dbh with a diameter tape versus a caliper will produce different upper stem values. Measurement of dbh with a caliper is highly recommended.

Both the Criterion 400 and Tele-Relaskop must be used with a sturdy tripod that has head leveling capabilities. A good quality, lightweight photographic tripod can be used with the Tele-Relaskop. Future enhancements to the Criterion 400 will hopefully reduce the weight and bulk of the necessary battery packs and large surveying-type tripod.

When measuring upper stem heights and diameters with either instrument, the user must be at a horizontal distance equal to 1.0 to 1.5 times the tree height on flat terrain or not exceed a 45° above or below the horizontal on steep terrain. Both the Criterion 400 and the Tele-Relaskop have maximum angle limitations of approximately 60°. The Criterion 400 will emit a beep if the maximum angle is exceeded. The Tele-Relaskop has no such warning and erroneous readings are possible.

The surveying and tree measurement capabilities of the Criterion 400 make it a more versatile instrument than the Tele-Relaskop, but potential users should evaluate each instrument on the basis of their requirements and intended usage.

LITERATURE CITED

Bitterlich, W. 1978. Single tree measurement by the Relaskop- A highly efficient tool for forest inventories. Paper for the 8th World Forestry Congress; 1978 October 16-28; Jakarta, Indonesia. FOB Postbox 12, A-5035 Salzburg, Austria.

Bitterlich, W. 1984. The Relascope Idea. Slough, England: Commonwealth Agricultural Bureaux, Farnham Rought. 242 p.

Bruce, D. 1975. Evaluating accuracy of tree measurements made with optical instruments. Forest Science. 21: 421-426.

Burkhart, H.E. 1977. Cubic foot volume of loblolly pine to any merchantable top limit. Southern Journal of Applied Forestry. 1(2): 7-9.

Byrnes, M.R.; Underwood, S.G.; Corbley, K.P. 1994. Losing ground: mapping Louisiana's disappearing coastline. GPS World, October:46-50.

Carr, B. 1992. Using laser technology for forestry and engineering applications. The Compiler. 10: 5-16

Carr, B. 1996. Using the Criterion 400 and Impulse 200 laser instruments to accurately measure trees. The Compiler. 14: 6-12

Clutter, J.L. 1980. Development of taper functions from variable-top merchantable volume equations. Forest Science. 26: 117-120.

Heske, B.; Parker, R.C. 1983. Collecting and processing forest data with the Tele-Relaskop and the microcomputer. In: Proceedings of International resource inventory conference; 1983 August. Corvallis, OR: University Press, Oregon State University: 714-717.

Jasumback, T.; Carr, W. 1991. Laser tree measurement. Timber Tech Tips 9124 2336-MTDC. Missoula, MT: U.S. Department of Agriculture, Forest Service.

LaBau, V.J. 1991. Tree height measurement indicator study. Performance of the laser height finder. FY92 Forest Health Monitoring Western Pilot Operations Report. Anchorage, AK: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest Research Station. 15 p.

Laser Technology, Inc. 1991. Tree measurement and survey laser, Operator's manual. Englewood, CO: Laser Technology, Inc. 48 p.

Laser Technology, Inc. 1992. Criterion 400 Survey Laser, Operator's Guide. Englewood, CO: Laser Technology, Inc. 125 p.

Liu, C.J. 1995. Using portable laser EDM for forest traverse survey. Canadian Journal of Forest Research. 25: 753-766.

Liu, C.J; Huang, X.; Eichenberger, J.K. 1995. Preliminary test results of a prototype of Criterion. Southern Journal of Applied Forestry. 19(2): 65-71

Matney, T.G.; Parker, R.C. 1992. Profile equations for several hardwood species to variable top diameter limits. Southern Journal of Applied Forestry. 16(2): 75-78.

Matney, T.G.; Sullivan, A.D. 1980. Inside and ouside bark taper equations for old-field plantation loblolly pine trees in the central Gulf Coastal Plain. MAFES For. Tech. Bul. 101. Mississippi State, MS. 28 p.

Matney, T.G.; Sullivan, A.D. 1982. Variable top volume and height predictors for slash pine trees. Forest Science. 28: 274-282.

Mesavage, C.; Girard, J.W. 1946. Tables for estimating board foot volume of timber. Washington, DC: U.S. Department of Agriculture, Forest Service. 94 p.

Moll, J.E. 1992. Development of an engineering survey method for use with the Laser Technology, Inc., tree laser device. Oregon State University, Department of Civil Engineering. 74 p. M.S. thesis.

Parker, R.C. 1983. TELE microcomputer software system. Jackson, MS: Forestry Suppliers, Inc.

Parker, R.C. 1997. Non-destructive sampling applications of the Tele-Relaskop in forest inventory. Southern Journal of Applied Forestry. 21(2): 75-83.

Parker, R.C. 1998. Field and computer application of Mesavage and Girard form class volume tables. Southern Journal of Applied Forestry. 22(2): 81-87

Pepling, A. 1995. Criterion series hand-held survey laser. Professional Surveyor, January/February: 30-31

Uren, J.; Garner, J. 1994. Criterion 400 hand-held laser- a break with tradition. Civil Engineering Surveyor, July/August.

Van Deusen, P.C.; Matney, T.G.; Sullivan, A.D. 1982. A compatible system for predicting the volume and diameter of sweetgum trees to any height. Southern Journal of Applied Forestry. 6(3): 159-163.

Wheeler, P. 1962. Pentaprism caliper for upper-stem diameter measurements. Journal of Forestry. 60: 877-878.

Development of the B.C. Vegetation Inventory Training Program

Norm Shaw

Abstract.—During the development of the B.C. Vegetation Resources Inventory, it was recognized that success would depend on the ability to implement and actually carry out the design. It was accepted that a training program would be an integral component of the inventory process. A formal process tied to basic principles of committee structure and recognition of work well done has provided a modular, competency-based program. To date, over 80 timber and ecology specialists have been trained and 60 have been certified. The program provides a means of developing and maintaining technical competency, identifying successes and shortcomings of the inventory design process, and serves to promote field-level careers in inventory implementation into the 21st century.

When I first agreed to participate in this conference, and before I had spoken with the two preceding speakers, I thought I would talk about the roles of field people in the design and implementation of a successful inventory. My involvement in the process is as a cruiser, a scaler, and an educator. I suggested in my original abstract that an inventory is a success not when the design is complete, but when it works. An inventory that works *will have* used academics, consultants, and the educational community as well as cruisers and other field practitioners throughout all stages of design, testing, and implementation. The previous speakers provided background to the B.C. Provincial Inventory and described the technical requirements, successes, and failures. Both speakers stressed that credibility has been and is an issue. Dr. Iles pointed out that virtually all difficulties encountered were people-related. If, as I suggest, an inventory is only a success when it works, it should be fairly apparent that cooperation and involvement by all participating groups is necessary. So, instead of pursuing the original topic, I will carry on where the previous speakers left off, and discuss the Provincial Vegetation Inventory training program and our experiences to date with its implementation.

WHY DID WE DO IT

The 1992 report by the Timber Inventory Task Force (TITF) stated:

> *"Inventory branch has put in very few field inventory plots in the last decade. Many of the experienced staff have moved on. There is a serious need for training, and for the anticipation of future developments in the Branch. Any new inventory will last a long time. Errors due to lack of training and quality control will occur. There will be a great need to develop career path specialists to direct the work....modify, interpret, recompile, and add to the next data set. It is important that training not just be oriented to Branch procedures, but to general principles and future options"* (TITF 1992).

The 1995 Vegetation Inventory Working Group (VIWG) said:

> *"training of field staff is a serious concern, and should be given a high priority." If....not provided ...could jeopardize the Vegetation inventory....only trained people should be employed..."* (VIWG 1995).

This need anticipated during the original Timber Inventory Task Force study and again during the work by the Vegetation Inventory Working Group was confirmed during the various field trials. It became apparent, especially during operational trials, that ad hoc training was not adequate.

A needs analysis was commissioned. The consultant contacted various stakeholders, confirmed training as a priority, and provided an indication of the market size.

WHAT WAS THE PROCESS/ COMMITTEE STRUCTURE

The process was overseen by a steering committee composed of members of the Vegetation Inventory Committee and its working groups.

Course material was developed by subject matter experts (S.M.E.'s) who were selected based on their extensive experience, credibility, and proven track record. The

---

Program Head of Forestry, British Columbia Institute of Technology, 3700 Willingdon Ave., Burnaby, British Columbia, V5G 3H2, Canada: Forestry Consultant, Norm Shaw and Associates.

subject matter experts were assigned topics that matched the provincial procedures manual, and they developed the curriculum under the guidance of the steering committee and a contract educational consultant.

All curriculum material was field tested during operational trials, and many modifications were made based on the feedback. Instructors were selected and the first course was delivered to the potential instructors by the steering committee and the S.M.E.'s who developed the material and who were ultimately responsible for it. Feedback from that firsthand exposure resulted in further and final modifications.

ASSUMPTIONS GUIDING THE PROGRAM DEVELOPMENT

During the training program development, there were a few assumptions or guiding principles.

It was assumed that the inventory sampling would start slowly, probably province-wide, to fully test the procedures. It was assumed that about 400 samples would be established annually for the first few years and that a crew of two would establish a single cluster sample in 1 day. An average 3-month field season would require about 10 crews or about 20 people to be trained each year for the first couple of years.

It was assumed that everyone collecting provincial data would be trained, certified, and competent. It was also assumed that the training would be free or tied to contracts so that contractors could write off the training expense. It was assumed that training would be a minimal financial burden to the contract community.

It was also assumed that the material would be in the public domain, available to colleges and universities, and that an instructional accreditation process would be developed to facilitate the eventual transfer of instructional responsibility to the educational community.

PRINCIPLES OF THE DEVELOPED TRAINING PROGRAM

All of the original assumptions survived the development stage, and a few more were added to the final product.

The concept that everyone collecting provincial data will be competent and certified through an evaluation process was re-emphasized. Competency is based on a demonstrated mastery of the Vegetation Inventory procedures and principles, not on previous experience, professional title, or membership in any professional organization.

The basis for training is the Provincial procedures manual, and any change to the procedures will be reflected in the training. Experience arising from training will be used for assessing future procedural modifications.

The procedures and the resulting training program are based on principles rather than rules, and the training will encourage participants to approach sampling problems laterally rather than in our traditional vertical manner.

The curriculum is Provincial and common to the entire province. The procedures will not change by region, but the applications will vary with the significant changes in climate, topography, vegetation, and forest health encountered from region to region. Local experts in soils, ecology, and forest health will supplement the instructional staff in each Forest Service region.

The course is modular and is normally delivered as a package. If modules are to be taken individually, they must be accompanied by an inventory overview and discussion of inventory and sampling procedures. Module material may not be de-coupled from the principles. Training is separated into two streams, one for timber and one for ecology. Individuals must receive "cross training" in the other's specialty before certification. Certification will follow the successful completion of all modules, field mentoring, and audited experience.

THE FINISHED PRODUCT

The training program is normally a 13-day *full program* made up of eight modules. The final 2 days are for evaluation and are a combination of written, oral, and field skills demonstrations. Four of the modules are common and must be taken by all participants; the remaining modules are specific to either the timber or ecology stream participants.

Modules

1.	Overview of the Veg Inv	timber and ecology
2.	Field orientation and navigation	timber and ecology
3.	Principles of sampling and plot est.	timber and ecology
4.	Inventory cruising	timber
5.	Call grading and net factoring	timber
6.	Plants, soils, and old growth	ecology
7.	Forage measurements	ecology
8.	Coarse woody debris	timber and ecology

Each module or course is accompanied by an introductory video, and the course materials are an extensive package of instructor guides, reference material, overheads, slides, participant guides, and example oral questions.

Challenge Program

Individuals are able to "challenge" the program pre-requisites or in some cases may actually challenge the individual modules or an entire stream.

Successful challengers to the pre-requisites participate in the full 13-day program, while module and stream challengers receive a 1-day theoretical overview, a 1-day integrated practice session, and then join the full participants for the final 2-day evaluation process.

The challenge program is based on a prior learning assessment (P.L.A.) process. The program assesses learning gained through experience, uses a simple portfolio approach, and relies on certified individuals "signing off" specified competencies.

The intention of using a prior learning evaluation is to recognize learning gained through experience, minimize occupational barriers and training duplication, focus on results rather than process, and contribute to self esteem by recognizing experiential learning.

DELIVERING THE TRAINING PROGRAM

Since the program was first delivered in 1996, there have been 8 training sessions, and 48 timber specialists and 19 ecology specialists have been certified.

The courses normally have between 15 and 20 people in them, usually more in timber than in ecology. The courses are delivered across the province and are coordinated through an outside agency.

During the first year, the instructor to staff ratio was very high. Initial courses ran with five instructors. Most recently, courses have been conducted with a lead instructor to coordinate and teach the challenge participants and another two instructors to teach the timber and ecology streams.

The course is usually delivered with the first three modules as common with both timber and ecology participants together. The streams are then split for discipline-specific instruction and brought together again for work as an integrated team.

Early courses were all full participation with no challengers present. The most recent courses have had more challengers than full participants.

Evaluation and Certification

As indicated earlier, certification is required to collect Provincial Inventory data. During the final 2 days of the training program the participant is required to take a written and oral examination and then demonstrate competency on all procedures.

Certification is currently issued module by module. Certified participants are eligible to work on Provincial Inventory projects where they will be "mentored" for 2 to 4 days and audited on a schedule based on audit results.

Mentoring

Mentoring of the participants after their training session is an integral part of the learning process. Competence is required, and it is recognized that competence is achieved through experience. A mentor who is experienced and respected provides guidance to the learner during the early stages of the operational sampling. Each graduate will be mentored 2 to 4 days depending on need and opportunity. The mentors provide confidential support, serve as role models, and provide nonjudgmental instruction and guidance.

Audit Program

The audit program was developed using a process similar to that of the original inventory. An independent contractor was hired to facilitate the process. The contractor formed a working group of experienced and respected field practitioners to develop the audit objectives, strategies, and procedures. Those procedures were put into draft form by the Forest Service and were reviewed by the working group, instructors, and regional staff before they were finalized.

The audit is used for contract control and inventory validation, and it serves as a training tool by providing early feedback to the sampling team. Audits are performed by trained and competent people. Each sampler is audited on a schedule that declines with success. The audit results are the final assessment of competency and may be used to recommend further mentoring, additional training, or the removal of certification.

HOW HAVE WE DONE WITH OPERATIONAL SAMPLING

The recommendations of the Vegetation Inventory Working Group were:

> *"The ministry of Forests should conduct this entire Inventory" and "These proposed Vegetation Inventory procedures should not be forced on groups who have historical data processes adequate to their own procedures for resource management" (VIWG 1995).*

A loss of funding has required the Forest Service to develop partnerships with "corporate inventories" to collect the Provincial Inventory samples.

There have been about 11 field projects since 1966. Some of the projects have been Forest Service initiated, coordinated, and supervised, but most are funded "corporate inventories" with a mixture of full VRI samples and "timber only" samples. The majority of the plots are "timber emphasis plots," but all plots must use Provincial Vegetation Inventory procedures and standards.

Currently, there are about 250 full VRI samples and about 1,500 timber only samples established in B.C. Data editing, database entry, and compilation are moving fairly slowly, especially for the full VRI sample data.

Most projects are carried out by licensees who are subcontracting the project supervision, project management, and field sampling. Typically, crews are two or three people with a timber specialist, an ecology specialist, and an assistant trainee. All but the trainee are certified and are on a mentoring and audit schedule.

WHAT WORKED FOR US

Developing principles or guidelines and sticking to them has worked.

It works to emphasize principles throughout training, mentoring, and auditing. Field people are learning to use common sense and to pay attention to the objective rather than simply follow rules.

Demanding that competency be demonstrated has worked. It has emphasized the commitment to accuracy and is sending a clear message that those who are certified have earned it, are proud of it, and intend to maintain the standards.

Using experienced, respected, and qualified people willing to work as subject matter experts, instructors, and mentors has resulted in a product that works in the field. Material developed and advice given by experienced and respected people is not challenged frivolously and tends to remain stable.

It worked when committees were able to meet often, work as a team, and not have alternate agendas.

The educational consultants worked well by being non-intrusive in technical matters and by providing 24-hour support for busy volunteer subject matter experts.

Assigning tasks appropriate to skills, attaching names to the final product, and giving written credit where it is due works.

It worked well for us to field test every proposed procedure several times and in varying conditions before accepting it as a procedure.

Following a formal process involving many is often painful until all parties have had their say and until everyone recognizes that the process is technical and not political. Eventually when only "workers" remain and everyone else has gone away happy and unthreatened, the work can be done. It works and the product will be supported.

Introducing the concept of "challenging" through demonstrated learning has stressed the idea that competency must be demonstrated and is not a matter of experience, position, or professional standing. It has been a slow process, but the forest workers, rich on experience and short on academics, are beginning to recognize that documenting learning for educational credit may be worth the trouble and effort.

Involving regional experts during training programs has provided credibility and local expertise.

Basing the instruction modules on a sound, principle-based, procedures manual has provided teaching boundaries and solid reference material.

Sticking to the idea that competency is not acquired through courses but must be developed through supervised practice is reinforcing the commitment to develop inventory professionals.

Competency-based evaluations and the requirement that Forest Service staff complete the same training and certification as everyone else send the appropriate message about commitment to standards.

It worked to use acknowledged experts (vs. specialists) to develop the audit objectives and strategies. It has provided an excellent starting point and will serve as principles and reference for the Forest Service.

Supporting the inclusion of ecological data supports integration and is a good idea. It gives "social" credibility to the program. Technical success will not be the only measure of inventory success. Credibility is an issue and society will demand the collection of information other than tree data.

Making procedures and training material available to educational institutions is a sure way to ensure provincial use of good, conceptually sound, material.

WHERE HAVE WE HAD PROBLEMS—SUGGESTIONS

Problems arise if you include, in the technical process, people not qualified to be there. It is appropriate to develop and test sampling procedures based on agency or individual concerns. It is a mistake to indulge the operational collection of data without the sponsoring agency demonstrating needs and participating in testing and operational use. Try the following:

> *Include people who "have a need"—sideline them from the technical input—it is not a consensus process; have them work as steering committees and liaison committees.*
>
> *Include field collection procedures only if the sponsors have field tested them (extensively) themselves; have sponsors teach the procedures before asking others to teach them.*

Moving to an operation level without first developing and testing data acquisition, database, and reporting tools creates problems:

> *If possible, don't go operational until the entire process is in place, and tested—start small—field crews quickly learn which data are real and which are speculative.*

It is a mistake to not completely involve those who will eventually implement the inventory:

> *Spend time during the design phase and definitely during testing to explain the objectives and process to regional or field supervisors.*

Problems will arise if agencies "in charge" exercise control through authority and generation of rules and when "being in charge" is the objective:

> *Only those qualified to be in charge should be; train those in charge, encourage an understanding of principle, discourage the proliferation of rules and vertical thinking, encourage initiative, and reward success.*
>
> *The people charged with responsibility must have authority and must be willing and able to use their judgment about principles and objectives; they must be informed, trained, and committed.*

An inappropriate field load will kill an inventory project:

> *Develop procedures for all data requirements; field test and perfect the procedures; remove excessive requirements; put some on the shelf for later use; recognize that inventory is a sample, not a site description; have data collection appropriate to conditions, time, and training; have the owners of the data collect the data—it may require you to declare ownership.*

It is a mistake to not have an effective communication process to immediately answer field concerns:

> *Provide a means for field supervisors to have their problems and concerns addressed and solved immediately; someone with authority must be available to SOLVE problems—not defer or pass them along; that person then should have the responsibility to take the change or issue to the procedure level and to the training program.*

Problems can be anticipated and technical changes can be handled appropriately if an independent overview technical steering committee is in place:

> *Maintain an independent group of experts to provide technical advice and keep individual technical issues in perspective.*

It is a good idea to view the inventory design as a set of tools to be used or not used as required. It is a mistake to require all of the tools to be used at all times, and it is a mistake to put broken tools back in the toolbox:

> *Train and educate field supervisors so that they will have the judgment and the authority to select the appropriate tools for use; do not allow bureaucrats to impose mandatory field procedures based on their inability to develop flexible edit and compilation routines; test and fix the procedures for any particular component before putting it away for future use.*

For many reasons, mostly economic, the slow controlled start of the Vegetation Inventory did not happen. The training plan anticipated a slow start with inventory samples being established, in fairly large sampling units, controlled by the Forest Service. It was anticipated that secure funding would allow projects to be identified enough in advance that contractors could advance bid and participate in training before the project start time.

Problems arose when funding shifted to the corporate side, and it was necessary to pursue the Provincial Vegetation Inventory in partnership with licensees. Licensees were required to use the VRI procedures for their corporate inventories.

Sampling unit sizes decreased, the number of samples increased, more people had to be trained, training objectives were different for corporate samples, and training could not be tied to specific projects. Contractors could not afford to send participants without secured contracts, project finalization often did not provide lead time to develop a course, skilled instructors were few and committed, and available contractors were not qualified for the training as designed.

It is proving difficult and expensive to develop qualified instructors when courses are seasonal and compete with other projects. There are not enough projects to warrant training a large group of instructors, and a small instructor group limits training flexibility.

We moved ahead of our ability to train, certify, monitor, and support the product. If the training is mandatory, it is the limiting factor.

Compromising on principles is not a solution:

> *Success requires that all the pieces work; don't impose field requirements that your training people can't handle.*
>
> *Competency-based programs require a certain skill level for entry; experience, credentials, or influence is not a substitute; stick to the pre-requisites—in the long run it will be respected and will provide necessary credibility.*

As Dr. Iles indicated earlier in "one of those.... modern inventories....the potential for disaster was enormous....however, we seem to have pulled it off (the design, that is—the *execution* is still very much up in the air.)"

The design is working and the procedures, with a few exceptions, are working. The methods that "had drifted off track" or were "wrong headed" have been largely banished. Participants of the training program have embraced the principles taught and seem willing to continue to do so. Field crews seem to understand a valid sample, they are wary of bias, they appreciate simple and sound collection methods, and they work hard at accuracy.

The inventory design, procedures, and the training program are a success, and the director of inventory is listening and seems willing to make changes as required.

If the de Morga's can step away and provide room for people who are capable and able to deal with the details, perhaps the implementation will succeed as well.

There is a need to define ownership of the inventory process so that the ecology sample size can be reduced and the one or two untested procedures can be fixed to avoid damaging the credibility of the majority of tested procedures.

The tedious and difficult behind-the-scene details need to be taken up by those concerned with doing the work rather than being in charge, and the process of communication with regions, districts, and industry must be restarted and expanded. A full record of the VIWG and training process; the submissions, discussions of technical issues, and decisions on those issues; and the recommendations for implementation should be prepared and used to clarify the intent, purpose, and limitations of the inventory design. The training program needs to be modified to address current realities. There is a need to de-couple the training from projects, and reduce the costs by providing individual module delivery during the off season and by developing alternate forms of delivery. The challenge program should be simplified and should provide short "upgrade" courses to facilitate program entry or, in some cases, to expedite the challenge process and reduce the demand for full training programs, and the details of certification and re-certification should be left to an educational institution or certifying association.

The real challenge to me, as an educator, is to move professionally prepared technical material into the colleges and universities. As our populations have grown and as our workforce requirements have changed, it has become socially necessary to enter the workforce as late as possible. School is a great place to keep people out of the work environment.

Few would argue that our time spent in school is time spent learning. We now spend 16 to 18 years earning credentials to gain an entry-level position in the workforce. Bachelor degrees are now required where high school diplomas were once adequate.

Unfortunately, the people with the bachelor's degrees and the universities don't know it. The graduate expectations don't match entry-level needs. Employers don't provide extensive on-the-job training, and the universities don't teach the technical material that would provide the skills for those entry-level positions. Our entry-level graduates do not expect to work their way up. They certainly do not expect to have careers as cruisers or as dirt foresters. In most cases, they do not have the technical skills even if they wished to do so.

The success of inventories and other field-based processes depends on professional field people. There must be careers for cruisers, field ecologists, and dirt foresters. Some continuity and stability in the field workforce is required. Over the long run, we will certainly not succeed by providing project-specific training programs. The skills, and to some degree the procedures, will have to be developed and learned during our ever increasing school time.

Technical material that is rooted in principle, that is prepared by competent experienced people, and that is field tested and found to work must find its place in our post-secondary curriculum.

ACKNOWLEDGMENTS

I would like to thank the reviewers: Dr. Kim Iles, Biometrician, Kim Iles and Associates Ltd., Nanaimo, BC, Canada, and Mike Fall, Brenton Forest Surveys, Ladysmith, BC, Canada.

LITERATURE CITED

TITF (Timber Inventory Task Force). 1992. Report of the Timber Inventory Task Force on the past timber inventory with recommendations for the future. Victoria, BC: The Executive Secretariat, Resources Inventory Committee.

VIWG (Vegetation Inventory Working Group). 1995. Final report from the Vegetation Inventory Working Group on a proposed new inventory. Victoria, BC: The Executive Secretariat, Resources Inventory Committee.

Using A Ceptometer to Validate A Visual Evaluation of the Degree of Defoliation of Holm and Cork Oak Trees

Margarida Tomé and Maria Vasconcelos

Abstract.— The study presented in this paper is part of a project to monitor the defoliation degree of cork and holm oak trees in stands with signs of "decline," after application of different amounts of Aliette, a product specific for *Phytophotora cinnamonii*, one of the possible causes of the "decline." The specific objective was to validate a qualitative classification of the degree of defoliation of cork and holm oak trees. This qualitative classification, visually assessed by an operator, is based on the degree of defoliation of tree crowns according to the EU Regulation nº 1697/87. Two quantitative variables were also used to evaluate the defoliation degree of 210 trees in each of three sites and therefore to validate the subjective classification: percentage of radiation (PAR) that is not intercepted by the crown ($\%rad_{nint}$), and leaf area factor (kL), an estimation of the product of leaf area and the extinction coefficient. The percentage of radiation non-intercepted by each crown was evaluated with the Sunfleck ceptometer by measuring the radiation under the tree crown and outside the canopy. Analysis of variance and the median, the Kruskal-Wallis test, and the Kolmogorov-Smirnov test were used to determine if there were significant differences between the values of these quantitative variables for trees classified in different defoliation classes. These analyses showed that, generally, there are significant differences for $\%rad_{nint}$ and kL across different defoliation classes, therefore giving some confidence to the subjective classification. It was also shown that the accuracy of the operator improved with practice.

Cork oak (*Quercus suber*) stands are among the more important forest types in Portugal, in terms not only of area but also of the economic value of cork and the importance of the ecosystem cork oak represents. Of the 3.4 million ha of forests in Portugal, 720,700 ha (21 percent of total forest area) are cork oak stands (DGF 1998). These stands produce 123,000 t of cork per year (mean for the years 1988/93); cork products account for 26 percent of the total forest products exported from Portugal (CESES 1996). Although economically not as important as cork oak stands, holm oak (*Quercus ilex* spp. *rotundifolia*) stands, with a total area of 475,700 ha (DGF 1998), are also of great environmental importance in a large area of regions with a semi-arid climate. The apparent "decline" of some cork and holm oak stands in Portugal has been one of the worries of the landowners, and several studies are being carried out on the subject. According to the survey that is being conducted in Portugal following the International Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP), the maximum levels of defoliation occurred in 1991 and 1992, with, respectively, 36.6 and 29.2 percent of the sampled trees with signs of defoliation (Barros and Rodrigues 1994). *Phytophotora cinnamonii* has been claimed as one of the possible causes for the "decline."

Between December 1992 and March 1993, the company Rhône-Poulenc Agro established some trials in cork and holm oak stands to monitor the effect of the application of different amounts of Aliette, a product specific for *Phytophotora cinnamonii*, on the vegetative situation of the oak trees with signs of "decline." Monitoring of these trials was based on an operator's observation and visual classification of the degree of defoliation of each individual tree crown into five defoliation classes, according to the EU regulation No 1697/87 (CEE 1987). The objective of the study reported in this paper was to evaluate the accuracy of the operator in visually assessing the degree of defoliation of the oak trees.

METHODS

Experimental Design

The trials designed to monitor the effect of the application of different amounts of Aliette on the vegetative situation of the oak trees with signs of "decline" were established on 18 sites. Aliette is a fungicide of Rhône-Poulenc origin with 80 percent of fosetil (in the form of fosetil of aluminum) that is used in other *Quercus* to fight

---

Associate Professor, Departamenta de Engenharia Florestal, Instituto Superior de Agronomia, Tapada da Ajuda, 1349-017 Lisboa, Portugal, and Agronomist, Rhone-Poulenc Agro Lda, Av. Duque de Avila, 185, 3°D, 1050 Lisboa, Portugal, respectively.

Phytophotora cinnamonii. Two of the trials were established in holm oak stands; the remaining ones in cork oak stands. These trials included, in each location, seven large stand areas (4 ha for the aerial and 7 ha for the terrestrial treatments) to which the following treatments were randomly assigned:

- 2 applications of 5 kg.ha^{-1} (aerial treatment)
- 3 applications of 5 kg.ha^{-1} (aerial treatment)
- 2 applications of 5 kg.ha^{-1} (terrestrial treatment)
- 3 applications of 5 kg.ha^{-1} (terrestrial treatment)
- 2 applications of 7.5 kg.ha^{-1} (terrestrial treatment)
- 4 applications of 5 kg.ha^{-1} (terrestrial treatment)
- control

The trials, established between December 1992 and March 1993 by the company Rhône-Poulenc Agro, were visited four times between the time of establishment and July 1994. All the trees inside each plot were observed, and the respective defoliation degree qualitatively assessed by the same operators. Three out of the 18 sites, Palma, Freixo, and Catapereiro, were selected for the validation of the subjective classification using a ceptometer, a device that measures incident photosynthetically active radiation (see below). The Palma and Catapereiro sites are cork oak stands and the Freixo site is a holm oak stand. Some years ago the acorns of the oaks were considered an economically important product and the trees used to be pruned to increase fruit yield (fructification pruning). This practice is still used by some farmers that associate this type of pruning with tree vigor and cork yield. Tree crowns in the Palma and Catapereiro sites had signs of previous pruning, particularly the Palma site, while tree crowns in the Freixo site were clearly unpruned. In each of the seven plots from each site, 30 trees, 10 in each of three defoliation classes (1, 2, and 3), were selected for measurement of non-intercepted radiation with the ceptometer. This quantitative evaluation of the degree of defoliation was made on two dates, July 1993 and July 1994. A total of 210 trees were measured at every site on each of the two evaluation dates. At the same time, the same operator qualitatively evaluated the degree of defoliation of these trees.

Evaluation of the Degree of Defoliation

Qualitative Evaluation of the Degree of Defoliation

The degree of defoliation of every tree was assessed by the same operator and put into one of the five classes defined according to the EU regulation nº 1697/87 (CEE 1987):

1. healthy tree, less than 10 percent defoliation;
2. light defoliation, 11-25 percent;
3. medium defoliation, 26-60 percent;
4. heavy defoliation, higher than 60 percent;
5. dead tree.

Quantitative Evaluation of the Degree of Defoliation

The Sunfleck ceptometer (Delta-T devices, undated) is usually used for indirect evaluation of leaf area index. Model SF-80 was used in this study. It has 80 light sensors for photosynthetically active radiation (PAR) placed at 1-cm intervals along a probe. When this probe is inserted under the canopy, a microprocessor scans the 80 sensors. In sample mode, as it was used in this study, the ceptometer displays a reading (an average of the readings of all the sensors) each time the sample button is pushed, and the operator chooses when to average accumulated readings and store them in memory. The percentage of radiation non-intercepted by each crown was evaluated with the Sunfleck ceptometer by measuring the radiation under the tree crown and the radiation above the canopy. Radiation under each tree (rad_{und}) was evaluated by the average of eight measurements with the ceptometer radially placed under the tree crown (center at the stem) at 45º angle intervals. Radiation above the canopy (rad_{abv}) was measured outside the canopy before every fifth tree, using a similar procedure (eight measurements at 45º angle intervals). The mean of radiation measured outside the canopy just before and after each group of five trees was used as the radiation value for these five trees. All the measurements with the ceptometer were made in the 2-hour period around solar midday and cloudy days were avoided. The trees selected for this study were of similar size. This ceptometer is not designed for measurements under individual trees, because it also measures lateral radiation. However, it was assumed that it was convenient for the present work because it was intended here for comparative purposes. Another problem related to the use of the ceptometer is the fact that it relies on the assumption that the canopy elements are randomly dispersed in space (Delta-T devices, undated). This is not true for the crowns of cork and holm oak trees if they have been severely pruned as is the case at two of the sites, as previously mentioned.

Quantitative evaluation of the degree of defoliation took place on two evaluation dates, June/July 1993 and July/August 1994.

Two quantitative variables were used to evaluate the defoliation degree of each tree to validate the subjective classification:

- Proportion of total radiation that is not intercepted by the crown ($\%rad_{nint}$)

$$\%rad_{nint} = rad_{und}/rad_{abv}$$

where rad_{und} and rad_{abv} are, respectively, the radiation under and above the crown. The greater the value of $\%rad_{nint}$, the higher the degree of defoliation.

- Leaf area factor (kL)

$$rad_{und} = rad_{total}\, e^{-kL}, \qquad (kL = -log(\%rad_{nint})$$

where k is the extinction coefficient, L is leaf area, and other symbols are as before. The leaf area factor is an estimate of the product of leaf area and the extinction coefficient. The smaller the value of kL, the greater the defoliation degree.

Statistical Analysis

To assess the effectiveness of the operator´s visual assessment of every tree and placement into one of five defoliation classes, the mean and median values of $\%rad_{nint}$ and kL were computed for each site and evaluation date, by defoliation class. On the second evaluation date, there were a few trees in defoliation classes 0 and 4, but the frequency in classes 0 and 4 was very small. Therefore, only three defoliation classes were considered: (1) light defoliation, <25 percent; (2) medium defoliation, 26-60 percent; (3) heavy defoliation, >60 percent.

Statistical tests were selected to determine if there were significant differences in the values of $\%rad_{nint}$ and kL between trees classified into different defoliation classes. Analysis of variance, the median test, and the Kruskal-Wallis test (e.g., Conover 1980) were used to test if the distribution of the quantitative variables had the same location parameter across the different defoliation classes. Analysis of variance is a parametric test and tests equality of means, while the others are non-parametric tests that analyze the equality of medians. The last are expected to be less sensitive to non-characteristic values of non-intercepted radiation that can be registered under tree crowns highly influenced by previous pruning. These tests are intended to be sensitive to differences in means and medians of the various populations tested, but they may be insensitive to other differences, in particular differences in variance. In fact, a wide disparity of variances may tend to hide the differences in means (Conover 1980). The Smirnov-type tests were therefore also selected to test if the distribution of the quantitative variables ($\%rad_{nint}$ and kL) was the same across the defoliation classes. According again to Conover (1980), these tests are not as sensitive to differences only in means, but they are consistent against a wider variety of differences and, therefore, are often more powerful if the differences in means are accompanied by differences in variances and other differences. Smirnov tests on more than two independent samples may be applied only to samples of equal size, because the tables for the case of unequal sizes have not yet been developed (Conover 1980). To avoid this problem, the two-sample Kolmogorov-Smirnov test was used to compare the distribution of the quantitative variables $\%rad_{nint}$ and kL for defoliation class 1 and a class combining defoliation classes 2 and 3.

RESULTS AND DISCUSSION

Table 1 shows, for each site in each evaluation date, the mean and median values of $\%rad_{nint}$ and kL computed by defoliation class. Figures 1 and 2 illustrate the relationship between the median value of these two quantitative

Table 1.—*Mean (median) values for $\%rad_{nint}$ and kL and respective number of observations (nobs) by defoliation class in 1993 and 1994*

Defoliation class	*nobs*	**June 1993** *%rad$_{nin}$*	*kL*	*nobs*	**June 1994** *%rad$_{nint}$*	*kL*
			Catapereiro Site			
1	56	0.189(0.155)	1.832(1.867)	122	0.168(0.123)	1.972(2.097)
2	65	0.161(0.141)	1.967(1.960)	63	0.212(0.173)	1.664(1.756)
3	68	0.198(0.180)	1.715(1.716)	4	0.396(0.399)	0.956(0.920)
			Freixo Site			
1	66	0.124(0.099)	2.281(2.308)	124	0.112(0.095)	2.343(2.356)
2	68	0.158(0.143)	1.966(1.943)	32	0.171(0.136)	1.900(1.994)
3	26	0.222(0.190)	1.611(1.662)	4	0.201(0.194	1.644(1.640)
			Palma site			
1	69	0.252(0.183)	1.633	132	0.229(0.195)	1.597(1.636)
2	70	0.271(0.240)	1.457	63	0.283(0.240)	1.383(1.429)
3	70	0.264(0.224)	1.514	14	0.328(0.305)	1.196(1.188)

Figure 1.—*Median values of percentage of non-intercepted radiation (%rad$_{nint}$) for the three defoliation classes: (1) light defoliation, <25 percent; (2) medium defoliation, 26-60 percent; (3) heavy defoliation, >60 percent.*

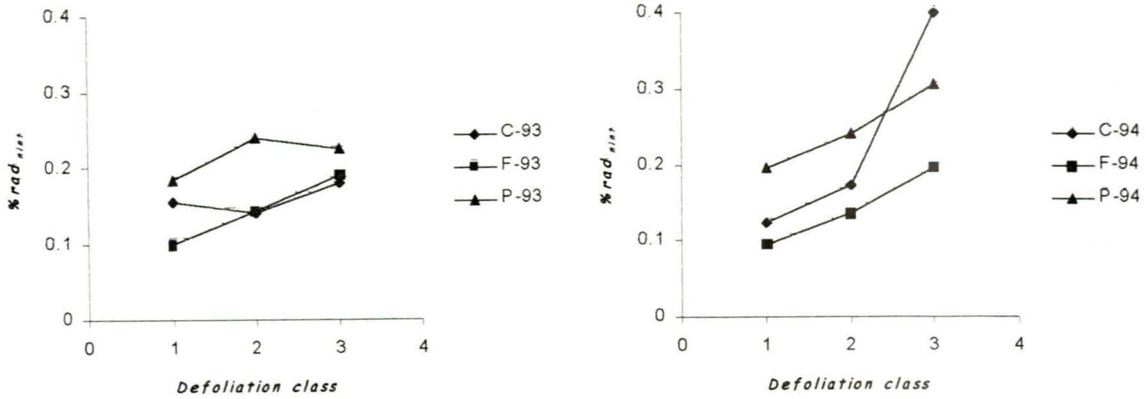


Figure 2.—*Median values of the product of extinction coefficient and leaf area (kL) for the three defoliation classes: (1) light defoliation, <25 percent; (2) medium defoliation, 26-60 percent; (3) heavy defoliation, >60 percent.*

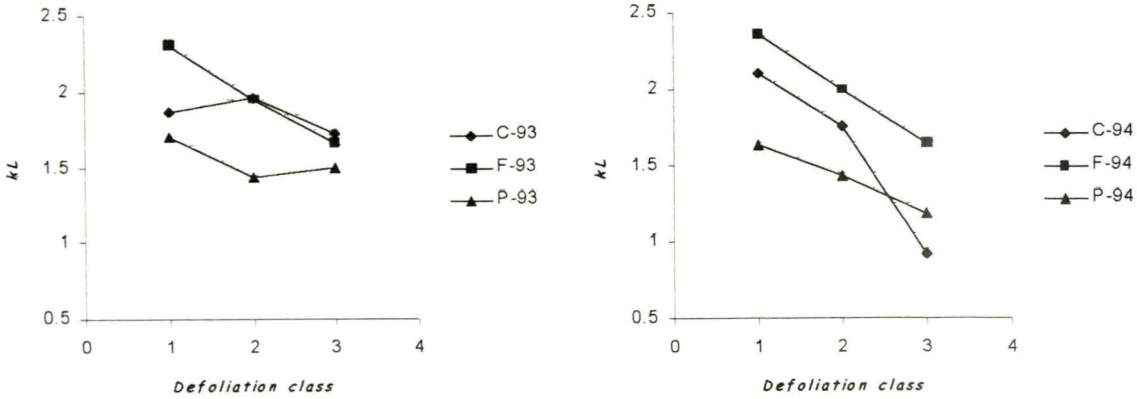


Table 2.—*Probabilities associated with the values obtained for the statistical tests to compare* %rad$_{nint}$ *and* kL *for different defoliation classes*

	Catapereiro		Freixo		Palma	
	Jul93	Jun94	Aug93	Jun94	Jul93	Jun94
			%rad$_{nint}$			
Analysis of variance	0.1078	0.0007	0.0001	0.0005	0.8477	0.0024
Kruskal-Wallis	0.0127	0.0001	0.0001	0.0001	0.2110	0.0015
Median test	0.0099	0.0001	0.0001	0.0005	0.0206	0.0044
Kolmogorov-Smirnov	0.8618	0.0001	0.0001	0.0002	0.0265	0.0046
			kL			
Analysis of variance	0.0194	0.0001	0.0001	0.0001	0.2370	0.0011
Kruskal-Wallis	0.0127	0.0001	0.0001	0.0001	0.2103	0.0016
Median test	0.0155	0.0001	0.0001	0.0005	0.0143	0.0060
Kolmogorov-Smirnov	0.8619	0.0001	0.0001	0.0002	0.0265	0.0511

variables and the defoliation class. As can be seen, there is a reasonable correspondence between the qualitative classification and the mean (median) values of the two variables. The ranking of the mean values of $\%rad_{nint}$ and kL for the three defoliation classes is almost always logical, only with two inversions for the Catapereiro and Palma sites in the first evaluation date (1993). The greater agreement between the qualitative classification and the quantitative variables observed in 1994 might reflect an improvement in the ability of the operator to visually assess the defoliation degree. These inversions, however, are not very important as they correspond to very similar mean values for adjacent defoliation classes. They may also be the consequence of one or two abnormally high values for non-intercepted radiation measured under a tree affected by previous pruning. Note that at the Freixo trial, established in a holm oak stand without signs of pruning, there is no inversion in the ranking of the mean values of quantitative variables. The results of the statistical tests (table 2) confirm the significance of the differences between the values of the selected quantitative variables for the three defoliation classes. The median test, less sensitive to abnormal values registered under pruned crowns, suggests significant differences for the three sites on the two dates, confirming that the mean may not be an appropriate statistic if there are pruned trees among the data set. From the two quantitative variables used, the leaf area factor (kL), an estimation of the product of extinction coefficient by leaf area, was more in accordance with the visual qualitative classification. This makes sense because this variable integrates two parameters that are greatly related to the degree of defoliation, the extinction coefficient and the leaf area.

CONCLUSIONS

The results obtained in the study reported here gave confidence to the operator who was in charge of the visual evaluation of the degree of defoliation, and the analysis showed also that visual assessment improved with training. The quantitative evaluation of defoliation degree through the measurement of non-intercepted radiation proved to be very useful for the validation of visual assessments. It can also be very important to train an evaluation team, guaranteeing homogeneity of classification. These conclusions are important, because for practical reasons, defoliation degree of individual trees in large areas has to be visually evaluated.

ACKNOWLEDGMENTS

The following people reviewed this manuscript: José A. Tomé, Teaching Assistant in the Department of Forestry, Instituto Superior de Agronomia, Lisboa, Portugal, and Klaus VonGadow, Professor, University of Göttingen, Germany.

LITERATURE CITED

Barros, M. da Conceição; Rodrigues, J.M. 1994. Evolução da vitalidade da floresta portuguesa desde 1988. III Congresso Florestal Nacional, Actas II: 62-79.

CEE. 1987. Jornal Oficial das Comunidades Europeias. Regulamento CEE nº 1696/87 e 1687/87 do Conselho, 10 de Junho de 1987. L 161, 22 de Junho de 1987, 28 p.

CESES. 1996. O sector florestal português. Conselho Ensino Superior-Empresa, Portugal.

Conover, W.J. 1980. Practical non-parametric statistics, 2nd ed. New York: John Wiley &Sons, Inc.

Delta-T devices. undated. Sunfleck Ceptometer. User manual. Delta-T devices. 27 p.

DGF. 1998. Resultados preliminares da 2ª fase da 3ª revisão do Inventário Florestal Nacional. Web site of DGF: http://www.dg-florestas.pt.

Aboveground Biomass Equations for 7-year-old *Acacia mangium* Willd in Botucatu, Brazil

Ricardo A. A. Veiga, Maria A. M. Brasil, and Carlos M. Carvalho

Abstract.—The biomass of stems, leaves, and branches was determined for 152 sample trees of *Acacia mangium* Willd were in a 7-year-old experimental plantation in Botucatu, Sao Paulo State, Brazil. After felling, dimensional measurements were taken from each tree. Cross sections were collected in 125 sample trees at ground level (0 percent), 25 percent, 50 percent, 75 percent and at the merchantable diameter top of 4 cm outside bark (100 percent). They were processed in the laboratory to establish the wood basic density and the bark density by maximum moisture method. Another 27 trees were separated into the crown components of branches and leaves, which were weighed green. Samples were collected to determine the dry mass/green mass ratios for branches and leaves. With the obtained data, seven linear regression models, based on diameter at breast height outside bark (d_i) and tree total height (h_i), were tested for the following dependent variables: total-stem wood dry weight outside bark ($tswob_i$); total leaves dry weight (tlw_i); total branches dry weight (tbw_i); total crown dry weight (tcw_i). The selected tree weight equations, based on residue distributions and values of coefficient of determination (r^2) and coefficient of variation (CV), were the following:

$$tswob_i = -44897 + 21327 d_i - 1973.229246 d_i^2 - 704.590913 d_i h_i + 107.485531 d_i^2 h_i$$
$$(r^2 = 0.9326,\ CV = 16.60\%)$$

$$\log_e tlw_i = -2.036212 + 1.732941 \log_e d_i + 1.903792 \log_e h_i$$
$$(r^2 = 0.7584,\ CV = 8.29\%)$$

$$tbw_i = 8397.141385 - 4064.638803 d_i + 484.543145 d_i^2 + 142.956321 d_i h_i - 20.611713 d_i^2 h_i$$
$$(r^2 = 0.8338,\ CV = 24.20\%)$$

$$\log_e tcw_i = 6.119424 + 2.242600 \log_e d_i - 0.857497 \log_e h_i$$
$$(r^2 = 0.8323,\ CV = 3.07\%)$$

where weight is given in g, diameter in cm, and height in m.

Planted only in experimental plantations in Brazil, the forest leguminous *Acacia mangium* Willd shows rusticity and fast growth in tropical countries (Nitrogen Fixing Tree Association 1987).

Although there are only a few national papers about *A. mangium*, studies in different knowledge areas about the species are beginning to be published. Among them, Silva *et al.* (1996) compared 18 provenances; Daniel *et al.* (1997) analyzed the phosphorus effect in seedlings; Carvalho *et al.* (1997) determined equations for estimates of wood weight inside bark; and Veiga *et al.* (1998) selected volume equations for *A. mangium* and for *Eucalyptus grandis.*

International scientific literature sums up some publications about the quantification of acacia biomass according to total dry weight: Lim (1985, 1986, 1988), Lim and Mohd-Basri (1985), Schubert and Whitesell (1985), Dudley and Fownes (1992), Bernhard-Reversat *et al.* (1993), Latif and Habib (1994), and Tanouchi *et al.* (1994). However, in some of these cases, the results came from small samples.

Schubert and Whitesell (1985) analyzed 28 species between 2 and 5 years old, verifying the good growth of *A. mangium* and its tendency to show multiple stems.

Lim (1985) selected samples from only six 3.5-year-old trees. He found a pattern of 64.1 kg total dry weight with a high correlation between the stem and the crown weight and the circumference at the breast height.

Professor, Department of Forest Science, FCA/UNESP, Universidade Estadual Paulista, 18603-970, Botucatu-SP, Brazil. Fax: (55)112520580. E-mail: raaveiga@unesp.br

Lim and Mohd-Basri (1985) determined the biomass over the ground of a group of 3.5-year-old *A. mangium*, reaching the medium value of 54.4 t/ha.

Lim (1996), in a fertilization test, found an annual pattern of 18.2 t/ha for an 11-tree sample, and in analyzing 4-year-old trees (Lim 1988) found 80.4 t/ha of total biomass over the ground.

Bernhard-Reversat *et al.* (1993) found a good correlation between dbh and the 7-year-old species total dry weight. Total biomass over the ground was between 120 and 130 t/ha, which is similar to the eucalyptus plantations in the same kind of soil.

Dudley and Fownes (1992) selected equations for 2-year-old trees. The weight estimation over the ground was determined according to only the dbh variable, because the height variable does not contribute significantly to the regression.

Latif and Habib (1994) selected weight equations, wishing to estimate the green weight of all the tree and the branches, stem, and leaves weights, and presenting conversion factors for total dry weight.

Tanouchi *et al.* (1994) determined the biomass of the 5-year-old trees, finding 147 t/ha.

In Brazil, there are a few studies about the subject. Among them are the work of Carvalho *et al.* (1997) about stem wood inside bark, and the research of Veiga *et al.* (1998) about volume equations.

Because of the lack of national studies, the studies that help to characterize *A. mangium* biomass total weight are very important. Thus, the importance of the present paper, about the selection of linear regression equations to estimate *A. mangium* total stem, leaves, and branches biomass weight, according to dbh outside bark and total height.

MATERIAL AND METHODS

A total of 152 sample trees were selected in a 7-year-old experimental plantation established in Botucatu, São Paulo State, with a 3- x 2-m original spacing.

Cross sections were collected in 125 sample trees at ground level (0 percent), 25 percent, 50 percent, 75 percent and at the merchantable diameter top of 4 cm outside bark (100 percent).

For each of the sample trees, the basic density of the wood was determined, based on correspondent values of total dry weight and the saturated volume, determined in a hydrostatic balance. The bark density was also calculated. From the field and laboratory data for each sample tree, the stem wood weight outside bark was calculated.

Another 27 trees were separated into the crown components of branches and leaves, which were weighed green. Samples were collected to determine dry mass/green mass ratios for branches and leaves.

For the selection of weight equations, the following dependent variables were studied: total-stem wood dry weight outside bark ($tswob_i$); total leaves dry weight (tlw_i); total branches dry weight (tbw_i); and total crown dry weight (tcw_i). The last one considers the sum of branches and leaves weights.

With obtained data, seven linear regression models, as showen in table 1, were used to estimate stem wood dry weight and crown components dry weight, as a function of tree diameter at breast height outside bark (d_i) and tree total height (h_i). The models were chosen among those used by Veiga (1984, 1992) and Timoni *et al.* (1997).

Table 1.—*Linear regression models tested for the estimate of tree biomass dry weight (y_i) as a function of the tree dbh outside bark (d_i) and the tree total height (h_i)*

Model	Equation
1	$y_i = b_0 + b_1 d_i^2 h_i$
2	$y_i = b_0 + b_1 d_i^2 + b_2 h_i + b_3 d_i^2 h_i$
3	$y_i = b_0 + b_1 d_i + b_2 d_i^2 + b_3 d_i h_i + b_4 d_i^2 h_i$
4	$y_i = b_0 + b_1 d_i^2 + b_2 d_i^2 h_i + b_3 d_i h_i^2 + b_4 h_i^2$
5	$\log_e y_i = b_0 + b_1 \log_e (d_i^2 h_i)$
6	$\log_e y_i = b_0 + b_1 \log_e d_i + b_2 \log_e h_i$
7	$\log_e y_i = b_0 + b_1 \log_e (d_i h_i^2)$

RESULTS AND DISCUSSION

The analysis of variance results corresponding to weight equations, i.e., linear regression models for estimates of total stem wood dry weight, total leaves dry weight and total crown dry weight, can be found in tables 2 and 3.

The estimated coefficients for the correspondent variables are in table 2. The values of coefficient of variation (CV) and coefficient of determinations (r^2) are in table 3. These results and observations about residue distributions were used to select the best model for each case.

The selected equations were the ones corresponding to Meyer's model, modified (equation 3), for the estimates of total stem wood dry weight outside bark, total leaves dry

Table 2.—*Parameter estimatives of linear regresssion models tested to determine the 7-year-old* A. mangium *biomass over the ground level in terms of total stem wood dry weight outside bark (tswob$_i$), total leaves dry weight (tlw$_i$), total branches dry weight (tbw$_i$), and total crown dry weight (tcw$_i$)*

Model	b_i	tswob$_i$	tlw$_i$	tbw$_i$	tcw$_i$
1	b_0	3435.408873	-193.501403	1423.520486	1230.019083
	b_1	15.046066	1.090259	3.248577	4.338835
2	b_0	13004	1139,724708	-277,115670	862,609038
	b_1	-63.013955	-39.020618	172.052003	133.031385
	b_2	-991.749450	-79.157732	-42.149921	-121.307653
	b_3	23.514248	3.488052	-6.300197	-2.812145
3	b_0	-44897	1698.027993	8397.141385	10095
	b_1	21327	-358.203968	-4064.638803	-4422.842771
	b_2	-1973.229246	-9.743085	484.543145	474.800060
	b_3	-704.590913	-1.026198	142.956321	141.930123
	b_4	107.485531	2.824350	-20.611713	-17.737363
4	b_0	12058	455.301419	-750.123922	-294.827503
	b_1	-310.823595	-74.156462	163.671762	89.515301
	b_2	23.458598	8.068715	-5.040747	3.027968
	b_3	15.268779	-2.992780	-0.979585	-3.972365
	b_4	-108.668268	12.274995	4.336672	16.611667
5	b_0	3.243866	-1.015015	4.321430	4.171388
	b_1	0.946525	1.113090	0.603098	0.650848
6	b_0	4.204248	-2.036212	6.487374	6.119424
	b_1	2.543616	1.732941	2.252351	2.242600
	b_2	0.069457	1.903792	-1.073971	-0.857497
7	b_0	3.753327	-1.907177	3.975191	3.778095
	b_1	0.807648	0.900005	0.473289	0.512817

Table 3.—*Results of coefficient of determination (r^2) and coefficient of variation (CV) for the models tested to estimate the 7-year-old* A. mangium *biomass over the ground level in terms of total stem wood dry weight outside bark (tswob$_i$), total leaves dry weight (tlw$_i$), total branches dry weight (tbw$_i$), and total crown dry weight (tcw$_i$)*

Model	tswob$_i$		tlw$_i$		tbw$_i$		tcw$_i$	
	r^2	CV%	r^2	CV%	r^2	CV%	r^2	CV%
1	.7324	32.68	.6499	54.11	.7448	28.13	.7908	27.09
2	.8967	20.47	.6753	54.32	.8216	24.52	.8239	25.92
3	.9326	16.60	.6817	54.99	.8338	24.20	.8332	25.78
4	.9305	16.87	.6859	54.64	.8215	25.08	.8247	26.43
5	.8276	3.00	.7531	8.21	.7221	3.80	.7750	3.48
6	.8994	2.30	.7584	8.29	.7990	3.29	.8323	3.07
7	.5673	4.76	.7583	8.12	.6848	4.04	.7409	3.74

weight, and total branches dry weight; and Shumacher-Hall's model (equation 6) for the total leaves dry weight and the total crown dry weight.

The weight equations selected in the conditions of the present study for biomass estimates of the 7-year-old *A. mangium* were the following:

$$tswob_i = -44897+21327d_i-1973.229246d_i^2-704.590913d_ih_i+107.485531d_i^2h_i \quad (r^2=0.9326,\ CV=16.60\%)$$

$$\log_e tlw_i=-2.036212+1.732941\log_e d_i+1.903792\log_e h_i \quad (r^2=0.7584,\ CV=8.29\%)$$

$$tbw_i=8397.141385-4064.638803d_i+484.543145d_i^2+142.956321d_ih_i-20.611713d_i^2h_i \quad (r^2=0.8338,\ CV=24.20\%)$$

$$\log_e tcw_i=6.119424+2.242600\log_e d_i-0.857497\log_e h_i \quad (r^2=0.8323,\ CV=3.07\%)$$

where the weight is given in g, diameter in cm, and height in m.

This results complement others found by the authors for the same species and age, corresponding to volume equations (Veiga *et al.* 1998) and total and merchantable stem wood weight inside bark equations (Carvalho *et al.* 1997).

CONCLUSION

The correspondent model to the Meyer's equation, modified,

$$y_i=b_0+b_1d_i+b_2d_i^2+b_3d_ih_i+b_4d_i^2h_i$$

was selected to estimate total stem wood dry weight outside bark and the total branches dry weight.

The correspondent model to the Schumacher-Hall's equation logarithmic combined variable

$$\log_e y_i=b_0+b_1\log_e d_i+b_2\log_e h_i$$

was selected to estimate total leaves dry weight and total crown dry weight.

ACKNOWLEDGMENTS

To FAPESP (Fundacao de Amparo a Pesquisa do Estado de Sao Paulo) and CNPq (Conselho Nacional de Desenvolvimento Cientifico e Tecnologico).

LITERATURE CITED

Bernhard-Reversat, F.; Diangana, D.; Tsatsa, M. 1993. Biomasse, mineralomasse et productivité en plantation *d'Acacia mangium* et A. auriculiformis au Congo. Bois et Forets des Tropiques, Montpellier, 238: 35-44.

Carvalho, C.M.; Veiga, R.A.A.; Brasil, M.A.M. 1997. Equations for dry weight estimation of seven-year-old *Acacia mangium* Willd bole in a southeastern brazilian forest plantation. In: Modeling growth of fast-grown tree species. Proceedings, Iufro Conference, Valdivia, Chile: 127-131.

Daniel, O. *et al.* 1997. Aplicaçao de fosforo em mudas *de Acacia mangium* Willd. Revista Arvore, Vicosa-MG, 21(2): 163-168.

Dudley, N.S.; Fownes, J.H. 1992. Preliminary biomass equations for eight species of fast-growing tropical trees. Journal of Tropical Forest Science, Kuala Lumpur, 5(1): 68-73.

Latif, M.A.; Habib, M.A. 1994. Biomass tables for *Acacia mangium* in the plantations in Bangladesh. Journal Tropical Forest Science, Kuala Lumpur, 7(2): 296-302.

Lim, M.T. 1985. Biomass and biomass relationship of 3.5 year-old open-grown *Acacia mangium*. Serdang: Faculty of Forestry, University Pertanian Malaysia. 13 p. (Occasional Paper 2). In: CAB Abstr. on CD-ROM (Wallingford*),* v.2, 1987-1989. (Abstract 890634886)

Lim, M.T. 1986. Biomass and productivity of a 4.5 year-old *Acacia mangium* in Sarawak. Faculty of Forestry, University Pertanian Malaysia. Pertanika, Selangor, 9(1): 81-87.

Lim, M.T. 1988. Studies on *Acacia mangium* in Kemasul Forest, Malaysia. I. Biomass and productivity. Journal of Tropical Ecology, Cambridge. 4(3): 293-302.

Lim, M.T.; Mohd-Basri, H. 1985. Biomass accumulation in a naturally lowland secondary forest and an *Acacia mangium* stand in Sarawak. Pertanika, Selangor. 8(2): 237-242.

Nitrogen Fixing Tree Association. 1987. *Acacia mangium* - a fast growing tree for the umid tropics. NFT Highlight. 87-04. 2 p.

Schubert, T.H.; Whitesell, C.D. 1985. Species trials for biomass in Hawaii: a first appraisal. Res. Pap. PSW-176. Berkley, CA: U.S. Department of Agriculture, Pacific Southwest Forest and Range Experiment Station: 1-13.

Silva, F.P.; *et al.* 1996. Avaliacao de procedencias de *Acacia mangium* Willd, aos 63 meses de idade, no Vale do Rio Doce-MG. Revista Arvore, Vicosa-MG. 20(3): 299-308.

Tanouchi, H.; *et al.* 1994. Size distribution and production structures of a secondary forest after selective cutting in the mixed dipterocarp forest, Brunei Darussalan. Bulletin of the Forestry and Forest Products Research Institute, Ibaraki. 366: 17-30.

Timoni, J.L.; Veiga, R.A.A.; Pinheiro, G. S. 1997. Determinacao de equacoes para quantificacao da biomassa da copa de arvores de *Eucalyptus saligna* smith aos 22 anos. Revista do Instituto Florestal, Sao Paulo. 9(1): 109-121.

Veiga, R.A.A. 1984. Dendrometria e Inventário Florestal. Fundacao de Estudos e Pesquisas Agrícolas e Florestais. Botucatu. 108 p.

Veiga, R.A.A. 1992. Tree models for biomass estimation in *Eucalyptus* and *Pinus* inventories in Brazil. The Finnish Forest Research Institute Research Papers, Helsinki. 444: 195-200.

Veiga, R.A.A.; Carvalho, C.M.; Brasil, M.A.M. 1998. Determinacao de equacoes de volume para arvores de *Acacia mangium* Willd e de *Eucalyptus grandis* Hill ex-Maiden. *Cerne*, Lavras (in print).

Data Management and GIS in Natural Resource Inventories

Distributing Stand Inventory Data and Maps Over a Wide Area Network

Thomas E. Burk

Abstract.—High-speed networks connecting multiple levels of management are becoming commonplace among forest resources organizations. Such networks can be used to deliver timely spatial and aspatial data relevant to the management of stands to field personnel. A network infrastructure allows maintenance of cost-effective, centralized databases with the potential for updating by distributed personnel. Using networks as a delivery medium also opens up the possibility for inexpensive sharing of data with relevant persons outside the organization: for example, the general public for a state agency. The software tools necessary to implement such an approach are described, as is one particular implementation as applied to geographic information systems and stand inventories.

Making good decisions requires that accurate, timely data and data analysis tools be readily available to all involved in the decisionmaking process. Today, the maps, imagery, and associated attribute data that fill this need for tactical and operational forest management planning can be effectively encapsulated in a geographic information system (GIS). A GIS allows easy integration of data sources and provides straightforward analysis capability (Prisley 1996). Two difficulties stand in the way of widespread use of GIS capability. GIS's are complex and the expertise for applying them is not typically broadly deployed throughout a forest management organization. A GIS is only as good as the data that constitute it. Because nature and resource management practices are dynamic, base GIS data must be continually updated and quality control measures applied. Both these concerns suggest a centralized staff model that is at odds with an effective management decisionmaking model.

The widespread use of intranets and the Internet to link personnel within forest management organizations (Burk 1995) provides an opportunity to address the disparity between optimal data management and decisionmaking models. Software tools were developed that allow creation of interfaces providing access to and analysis of spatial and aspatial data stored on centralized servers. The Internet World Wide Web (WWW) client/server model was used as a basis so that the resulting applications operate in the commonly understood WWW browser environment. Such a solution allows centralized control or centralized-mediated control of data quality without sacrificing effective data access.

The ForNet project, out of which software and application developments grew, is first summarized. The software tools themselves are then described, as is a prototype application for forest stand inventory. Ongoing software development directions are outlined, as is the availability of the software tools. Additional information about the project, applications, and software can be found at the ForNet WWW site (http://www.gis.umn.edu/fornet).

THE ForNet PROJECT

The ForNet project was a collaborative effort between the Department of Forest Resources, College of Natural Resources, University of Minnesota, and the Minnesota Department of Natural Resources, Division of Forestry (DNR-Forestry), with funding provided by National Aeronautics and Space Administration (NASA) through the Public Access to Remote Sensing Data program. The goal of ForNet was to research use of the Internet for delivering spatial data, particularly satellite imagery and associated ancillary data, as well as analytic tools to on-the-ground forest managers. DNR-Forestry has a long history of applying the latest technological solutions to management problems on their land, including the use of satellite remote sensing data (Bauer *et al.* 1994). This tradition sped ForNet efforts and led to the operational implementation of several successful ForNet prototype applications (cf. http://www.ra.dnr.state.mn.us/).

As part of an initial needs assessment effort, ForNet personnel identified three overlapping areas for which solutions and delivery mechanisms were needed in DNR-Forestry management planning:

- Image Delivery Systems
- GIS Data Services
- Information Resources

Image Delivery Systems work focused on raster data such as satellite imagery and digitized aerial photography. Prototype solutions were developed that allow map-based retrieval and viewing of images and photographs from

---

Professor of Forest Resources, University of Minnesota, 1530 Cleveland Avenue North, St. Paul, MN, USA.

large databases of materials over the Internet. Landsat Thematic Mapper (TM), Advanced Very High Resolution Radiometer, and scanned color infrared aerial photography data have all been dealt with. DNR-Forestry personnel can use Image Delivery Systems solutions to retrieve image data of specific interest to them. GIS Data Services addresses both the delivery of data in a GIS-ready-to-use format and the development of customized, on-line GIS capability. The former work allows selection and sharing of data layers of broad-scale interest within DNR-Forestry. Availability of customized GIS capability over the Internet allows field offices, many without high-end technology resources, access to data sources useful in their day-to-day work. Image Delivery Systems and GIS Data Services efforts stressed development of basic tools for delivering data and analysis solutions. Early in the ForNet project we ascertained the importance of enlisting self-selected DNR-Forestry personnel in applying information technology solutions to very specific problems they were interested in. This created a pool of motivated "early adopters" that were used to evangelize to their colleagues. Such efforts fell under the Information Resources component of ForNet.

The successes of ForNet have come about both because a need existed for which new technology could provide the solution and because researchers and practitioners worked collaboratively throughout the project. Collaboration took place because researchers wanted to develop products that would be used in practice and because practitioners were open to new approaches. This seemingly straightforward circumstance seems the exception rather than the rule when considering past technology developments in forest resource management. Without this "end-to-end" collaboration, the operational implementation of research prototypes to a full statewide basis would never have occurred, and future development possibilities would have been stymied. Given the success of the project, NASA has chosen to fund additional development for an additional 5 years.

SOFTWARE DEVELOPMENTS

Currently, ForNet software tools consist of three pieces. *MapServer* provides the capability to interact with vector data. *ImageView* provides similar capability for raster data. JavaScripts and Java applications provide the glue linking *MapServer* and *ImageView* as well as additional user interface control functionality.

Several requirements were specified at the development stage of the software. The software needed to work directly with the GIS and satellite imagery data formats used for general applications. Maintaining separate data systems for localized versus distributed applications would be impractical and fraught with error. The software would need to create views "on-the-fly"; relying on a database of canned views would greatly limit the usefulness of any resulting system. Since a WWW client/server model was to be employed, the software must be capable of converting results to WWW-compatible graphic formats such as GIF's or JPEG's. Any particular application would have specific requirements in terms of display and analysis functionality. The software would need to provide a mechanism for flexible creation of interfaces allowing simple extent and layer control. Since the attribute data behind the spatial data are often of equal import, access to these data would also need to be provided.

Based on these requirements, an interesting evolution of development philosophies took place. Initially, solutions were developed that were simply Common Gateway Interface (CGI) hooks into server-residing, canned GIS, and satellite image processing software packages. Such a solution proved to be limited both in terms of response time and scalability. This initial approach evolved into stand-alone CGI programs that accessed data in native formats, completed the necessary processing and conversions, and displayed the results in a static browser window. This approach was limited in terms of the integration of vector and raster data as well as the provision of effective user control mechanisms. When Java came on the scene, a new paradigm was adopted. Image servers were written and all processing and display capability moved to the client side. While this worked reasonably well for vector data, large raster data sets, as is commonly the case with extensive satellite imagery, were problematic. Further, the necessary Java applications were quite large, requiring significant computer resources of the client. In the end, a solution combining server and client computing capability proved most effective. Such a solution allows efficient use of computing resources, integration of multiple data types, and development of intuitive user-control capability.

MapServer

MapServer is a CGI program that provides the capability to work with vector GIS data. *MapServer* runs in conjunction with a WWW server. It has been implemented on various Unix versions, including Linux, as well as Windows NT. Currently, *MapServer* works directly with the shapefile format made available by ESRI (ESRI 1995) in conjunction with their Arc and ArcView software. Template files are used to specify data layers of interest, display characteristics, and WWW interface layout for any instantiation of *MapServer*. A typical implementation of *MapServer* consists of recursive calls with results built-up sequentially. A request is initiated by users through their (*MapServer*-created) browser interface. *MapServer* retrieves and combines the necessary shapefiles and creates a GIF image. The image and associated results can be returned embedded in hypertext markup language (HTML) code or as a uniform resource locator. Shapefiles can also contain attribute data; *MapServer* can thus be used to create map-based query interfaces to such data.

MapServer is highly extensible but provides several important baseline features including:

- scale-dependent drawing and labeling
- feature-based access to attribute data
- "GET" or "POST" CGI access
- automatic legend and scalebar creation
- configurable reference map
- support for tiled data
- "on-the-fly" projection conversion
- true type font support
- shapefile indexing

These and additional features can be seen in the prototype applications at the ForNet WWW site.

The shapefile format was chosen based on the popularity of ESRI products among the target user community (resource management organizations). Other formats could be implemented as well. The shapefile specification is in the public domain, so it is easy to move data to and from the format. Each shapefile corresponds to a map layer or coverage. No topology is attached to the shapefile reducing storage requirements and drawing overhead. A shapefile actually consists of a triad of files: one containing feature vertices, one containing feature attributes, and one containing an index.

ImageView

Like *MapServer*, *ImageView* is a gateway to spatial data. With *ImageView* the spatial data are raster images stored using the ERDAS Imagine file format (ERDAS 1994). ERDAS Imagine files were chosen for several reasons: (1) libraries necessary to read and write the files are publicly available, (2) the format is designed to handle multi-spectral image data and its spatial attributes, and (3) Imagine supports the creation of "pyramid" layers, reduced resolution images that allow for rapid creation of views at reduced resolutions. The *ImageView* image server is a CGI program built on the *MapServer* framework to handle user requests; an ancillary utility program creates WWW-compatible graphics as JPEG's or progressive JPEG's from Imagine files. Parameters such as band selection, data scaling, and areal extent can be set. Additional analysis capability is accessible through the ERDAS Imagine tool kit. Support for 8-bit image data in truecolor, grayscale, or pseudocolor modes is provided. Extensions of base *ImageView* capability allow simultaneous manipulation of multiple images, data extractions for downloading, and full integration within *MapServer* frontends.

Java Enhancements

The server-residing software, *MapServer* and *ImageView*, provides the horsepower for manipulating base spatial data and creating "on-the-fly" views in WWW-compatible formats. Given the disposition of such software, its capability for producing intuitive interface control mechanisms is limited. A need also exists to combine the outputs of the vector and raster data engines so that truly flexible "executive GIS's" can be produced.

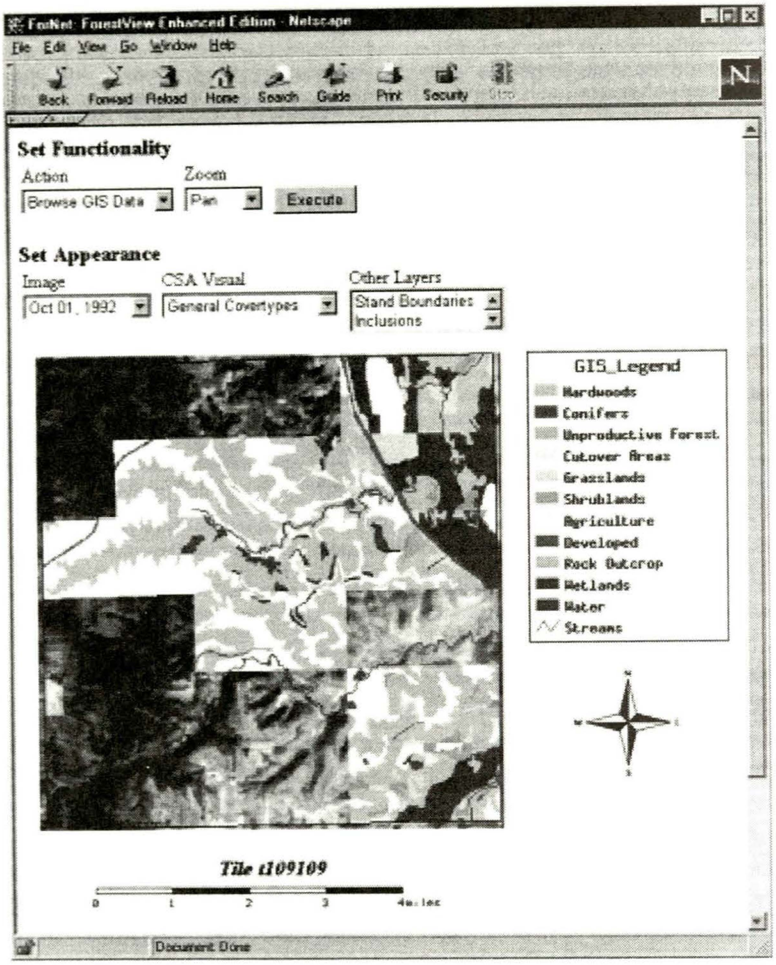
Java fills these identified needs. JavaScripts can be directly embedded into *MapServer* template files so that separate vector and raster coverages can be requested, integrated, and manipulated in the output interface. Java applications, residing on the client, can be used to enhance control through selection, panning, and zooming of spatial data as well.

THE ForestView APPLICATION

Forest resource management organizations routinely conduct in-place inventories of their holdings. These data are a primary source of information for tactical and operational planning. Given the dominant role of location in such efforts, many organizations manage in-place inventory data using GIS's. The GIS allows manipulation and display of important spatial data layers and query of associated aspatial data: most commonly stand attributes including timber characteristics.

A prototype system for accessing stand examination data via the Internet was built for DNR-Forestry as part of ForNet: ForestView. A simple image map allows the user to choose a particular township of interest within Minnesota. Upon selecting a township of interest, a map of stands in the township is presented in an interface that allows simple GIS tasks to be applied to the data (fig. 1). At present that capability includes choosing between map types (cover types, tree size classes, topography), particular map layers (stand boundaries, inclusions, roads, section lines), as well as panning and zooming of the map. Figure 2 displays the results of zooming in 3x on a particular conifer stand of interest. A backdrop of TM data, produced through a simultaneous call to *ImageView*, provides the means for placing DNR-Forestry holdings within the context of all ownerships; alternative TM dates can be selected as well. Once a stand of interest is located, its inventory attributes can be retrieved with a simple mouse click (fig. 3). To aid in interpreting the attributes, inventory reports include URL's to detailed descriptions and definitions of attribute labels.

The entire ForestView system runs on top of *MapServer* software. Work is currently underway to link this system to a growth model, allowing projection of stand attributes through time. The system is not intended to replace the


ForNet: ForestView Enhanced Edition - Netscape
File Edit View Go Window Help
Back Forward Reload Home Search Guide Print Security Stop
N
Execute
GIS_Legend
Hardwoods
Conifers
Unproductive Forest
Cutover Areas
Grasslands
Shrublands
Agriculture
Developed
Rock Outcrop
Wetlands
Water
Streams
N
W
E
S
0
1
2
3
4 miles
Document: Done

Set Functionality

Action: Browse GIS Data

Zoom: Pan

Set Appearance

Image: Oct 01, 1992

CSA Visual: General Covertypes

Other Layers: Stand Boundaries, Inclusions

Tile t109109

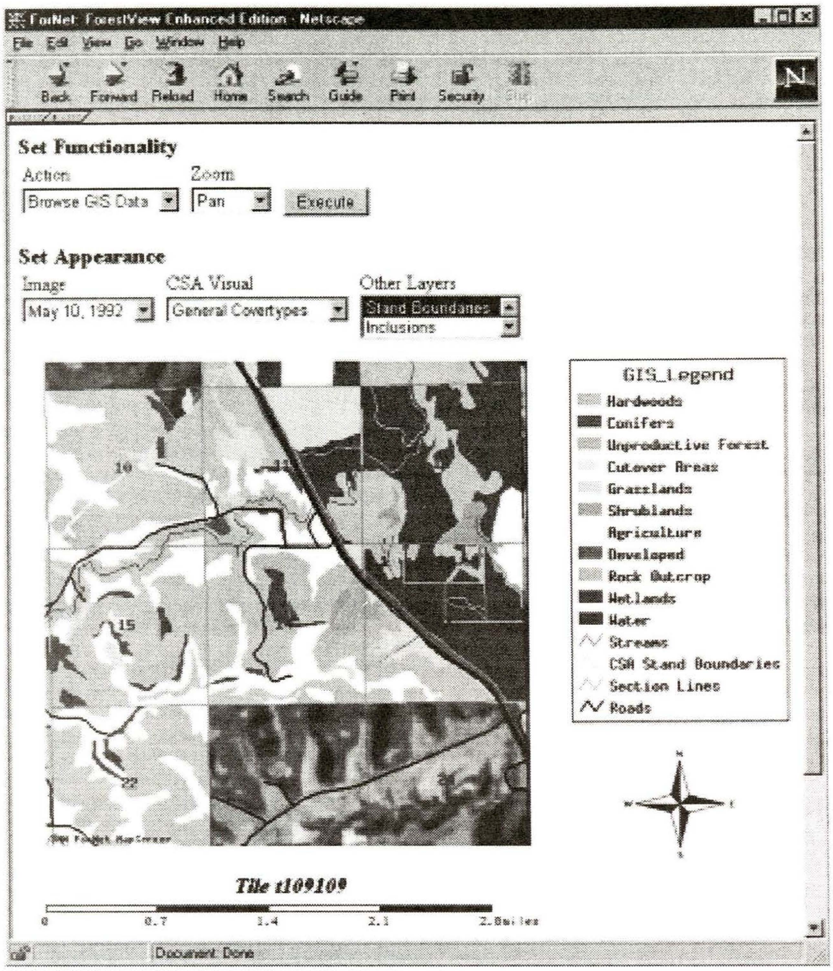
Figure 1.—*ForestView interface showing forest stands in a township with GIS data and a TM backdrop.*

use of GIS's but to instead deploy simple GIS capability to a broader audience of users. Since the application requires only commonly available WWW browser software, technology requirements are much reduced over those of a full-blown GIS. DNR-Forestry has made their entire statewide stand inventory database available to the public via the Internet. The ForestView implementation allows centralized maintenance of GIS data sources, an approach preferred by many organizations. A planned extension of the application will allow updating of spatial and aspatial data by distributed agency personnel through the WWW interface.

CONTINUING SOFTWARE DEVELOPMENT

A current direction for enhancement of the ForNet software tools is the addition of more general analysis capability. For example, *MapServer* can be used to create spatial displays and return attribute data with coordinate information attached. JavaScripts allow user control of the extent for which result data are returned. Server and/or client residing analysis modules can grab the result data and return HTML-formatted output. For simple processing, such functionality can be provided by JavaScripts within *MapServer* template files. More sophisticated requests, such as geostatistical calculations, require invocation of separate applications. Java-based statistical tool kits such as provided by the new XGobi environment (cf. Cook *et al.* 1997) could be easily integrated into the framework described. Basic GIS processing can also be added through such an approach including proximity analysis, overly analysis, and buffering.

Figure 4 displays a simple implementation of these ideas. A *MapServer*-generated interface is used to display data on waterfowl production areas and other relevant layers for western Minnesota (in figure 4 an area of interest has been zoomed in on). Java code allows the user to set a point buffer by clicking a point that is used in combination with a selected buffer distance; the result is the circle shown in figure 4. *MapServer* returns the attributes of the selected features within the buffer area, which are in turn processed by a Java application to summarize, in this



Set Functionality

Action: Browse GIS Data

Zoom: Pan

Set Appearance

Image: May 10, 1992

CSA Visual: General Covertypes

Other Layers: Stand Boundaries, Inclusions

ForNet: ForestView Enhanced Edition - Netscape
File
Edit
View
Go
Window
Help
Back
Forward
Reload
Home
Search
Guide
Print
Security
Stop
Execute
10
11
15
22
GIS_Legend
Hardwoods
Conifers
Unproductive Forest
Cutover Areas
Grasslands
Shrublands
Agriculture
Developed
Rock Outcrop
Wetlands
Water
Streams
CSA Stand Boundaries
Section Lines
Roads
N
W
E
S
Tile t109109
0
0.7
1.4
2.1
2.8miles
Document: Done

Figure 2.—*ForestView interface from figure 1 zoomed in by a factor with stand boundary, roads, and section layers turned on.*

case, area and perimeter of lakes (cf. scrollable dialog). Analysis capability can be targeted or made quite general within this *MapServer*-centered analysis framework.

SOFTWARE AVAILABILITY

MapServer and *ImageView* are distributed according to the open source concept. Each package requires use of other freeware or public domain code. Code, documentation, and test applications are available at the ForNet WWW site. We hope that open source distribution will encourage others to add functionality to the packages and share those results broadly. This has already happened. Open source also facilitates employing a distributed server environment, important for applications based on, for example, country-wide databases. Two basic Java applications can also be made available that provide integration and additional user interface control.

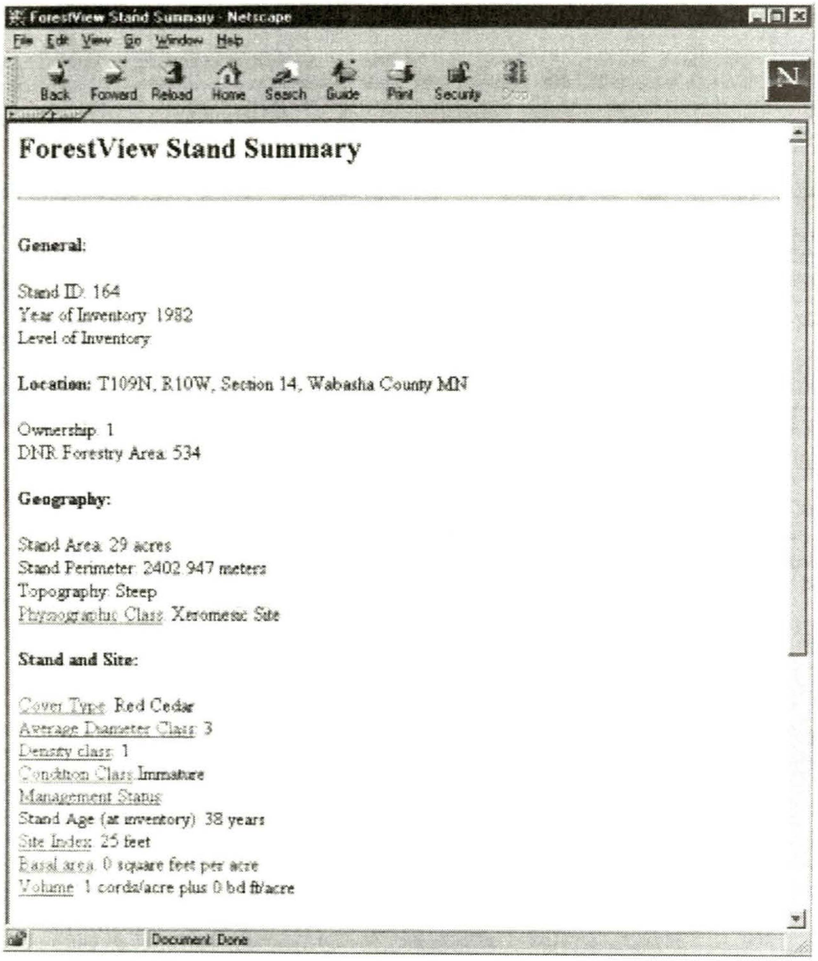
ACKNOWLEDGMENTS

Research supported by the National Aeronautics and Space Administration through grants NAG5-2698 and NCC-316 and by the Agricultural Experiment Station, University of Minnesota, through project MIN-42-044. Mr. Kirk Bloomquist prepared the figures in the article.

The manuscript was reviewed by Dr. Dietmar Rose and Mr. Hector Franco-Lopez, Department of Forest Resources, University of Minnesota, St. Paul, MN, USA.

LITERATURE CITED

Bauer, M.E.; Burk, T.E.; Ek, A.R.; Coppin, P.R.; Lime, S.D.; Walsh, T.A.; Walters, D.K.; Befort, W.; Heinzen, D.F. 1994. Satellite inventory of Minnesota forest resources. Photogrammetric Engineering and Remote Sensing. 60(3): 287-298.


ForestView Stand Summary - Netscape
File Edit View Go Window Help
Back
Forward
Reload
Home
Search
Guide
Print
Security
Stop
Document: Done

ForestView Stand Summary

General:

Stand ID: 164
Year of Inventory: 1982
Level of Inventory:

Location: T109N, R10W, Section 14, Wabasha County MN

Ownership: 1
DNR Forestry Area: 534

Geography:

Stand Area: 29 acres
Stand Perimeter: 2402.947 meters
Topography: Steep
Physiographic Class: Xeromesic Site

Stand and Site:

Cover Type: Red Cedar
Average Diameter Class: 3
Density class: 1
Condition Class: Immature
Management Status:
Stand Age (at inventory): 38 years
Site Index: 25 feet
Basal area: 0 square feet per acre
Volume: 1 cords/acre plus 0 bd ft/acre

Figure 3.—*Result of clicking on the conifer stand in the center of figure 2: attribute data for the stand coded in HTML.*

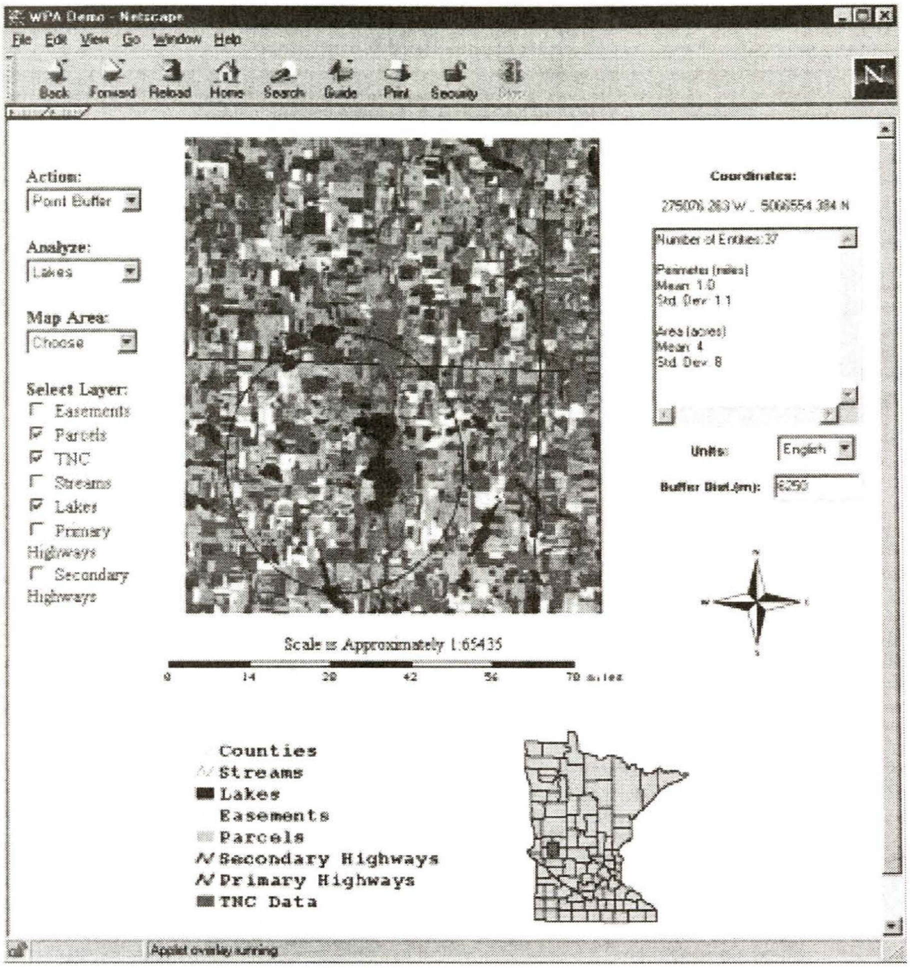
Burk, T.E. 1995. Forestry on the Internet: an introduction. Journal of Forestry. 93(5): 6-7, 50-54.

Cook, D.; Symanzik, J.; Majure, J.J.; Cressie, N. 1997. Dynamic graphics in a GIS: more examples using linked software. Computers and Geosciences: special issue on Exploratory Cartographic Visualization. 23: 371-385.

ERDAS. 1994. ERDAS field guide. Atlanta, GA: ERDAS, Inc.

ESRI. 1995. ArcView shapefile technical description. ESRI White Paper Series. 14 p.

Prisley, S. 1996. Westvaco's forest resources information system. The Compiler. 4(3): 4-8.


WPA Demo - Netscape
File Edit View Go Window Help
Back Forward Reload Home Search Guide Print Security
N
Counties
Streams
Lakes
Easements
Parcels
Secondary Highways
Primary Highways
TNC Data
N
W
E
S
Applet overlay running

Action: Point Buffer

Analyze: Lakes

Map Area: Choose

Select Layer:
- ☐ Easements
- ☑ Parcels
- ☑ TNC
- ☐ Streams
- ☑ Lakes
- ☐ Primary Highways
- ☐ Secondary Highways

Coordinates:

275076.263 W , 5066554.384 N

Number of Entities: 37

Perimeter (miles)
Mean: 1.0
Std. Dev: 1.1

Area (acres)
Mean: 4
Std. Dev: 8

Units: English

Buffer Dist.(m): 6250

Scale is Approximately 1:65435

0 14 28 42 56 70 miles

Figure 4.—*Example of analysis capability added to MapServer through Java applications.*

DataPlus™—A Revolutionary Applications Generator for DOS Hand-Held Computers

David Dean and Linda Dean

Abstract.—DataPlus allows the user to easily design data collection templates for DOS-based hand-held computers that mimic clipboard data sheets. The user designs and tests the application on the desktop PC and then transfers it to a DOS field computer. Other features include: error checking, missing data checks, and sensor input from RS-232 devices such as bar code wands, calipers, electronic balances, GPS receivers, laser rangefinders, and water quality transmitters. DataPlus is developed for the nonprogrammer, yet robust enough for the professional software developer. DataPlus was designed with natural resource data collection in mind.

For many years forest managers have been aware of the benefits of using hand-held computers. Their cost effectiveness, portability, ruggedness, speeding the time from field to data analysis, and improved data integrity are well known.

Through the years the hand-helds have evolved from proprietary operating systems to standard DOS operating systems. However, software is still a dilemma. Custom software can be costly, and time consuming, and it needs to be developed and supported by a programmer. Most standard DOS programs require large amounts of memory, have desktop applications in mind, and do not take small display sizes into consideration.

DataPlus eases the software dilemma. It is designed specifically for field data collection applications, taking into account the hand-held constraints. It is also developed for the nonprogrammer, but robust enough for the professional software developer.

DataPlus allows the user to easily design data-collection templates that mimic clipboard data sheets. It supports many features to customize your application including error checking of data and serial input from external devices. Since the applications generator is Windows-based, the data-collection templates are built using familiar, user-friendly setup screens. The templates resemble the rows, columns, and column headings used in PC spreadsheet programs. Once the application is defined and tested, the template setups are loaded into the hand-held computer for use in the field.

This paper describes the features of two versions of DataPlus. DataPlus For DOS and the newest version called DataPlus Professional. DataPlus Pro has everything that DataPlus For DOS offers but adds features that software developers and information systems managers will appreciate and have requested.

DATAPLUS FOR DOS OVERVIEW

DataPlus For DOS includes three separate programs:

1. Data collection software used with DOS-based hand-held computers.
2. A Windows-based applications generator for the PC. It is used to customize applications for the hand-held.
3. Communications software package, called DataPlus Host, used for transferring the collected data between the host computer and the remote hand-held.

DataPlus For DOS is compatible with most DOS-based IBM compatible hand-held computers. Supported display sizes range from 6 to 25 lines and from 20 to 80 columns. Two hand-held versions are included: one is for use with a 286 or greater processor and the other version is for 8088 or greater processors. Minimum hand-held hardware configurations include DOS 3.1 or greater, 540K of free RAM, and 500K of free disk space. Minimum hardware configurations for the PC include Windows 3.1 or greater, 4 Meg of RAM, and 3 Meg of free hard disk space.

DataPlus can be set up in a variety of ways, from basic to very complex, through the following features:

1. Provides one or two data levels for numeric or character columns.
2. Data entry types beyond keyboard such as serial devices and timers.
3. Facilitates automatic data entries to avoid repetitive keyboard input.
4. Facilitates data validation through a system of error checking.

President and Technical Services Manager and VP/ Marketing and Sales, respectively, Electronic Data Solutions, Jerome, ID, USA, developer of DataPlus.

5. Ensures that data are entered by checking for missing data.
6. Presents data in a wide variety of ways according to the user's needs.
7. Allows the order in which data are entered to be controlled according to the data already entered.
8. Provides a variety of search methods.
9. Transfers data and applications between PC and handheld computers through a direct or modem connection.
10. Stores data in Xbase style DBF formats.
11. Converts Xbase style DBF formats to ASCII files.
12. Allows testing of the application on the PC before using it in the field.

DEFINING AN APPLICATION

Data Format

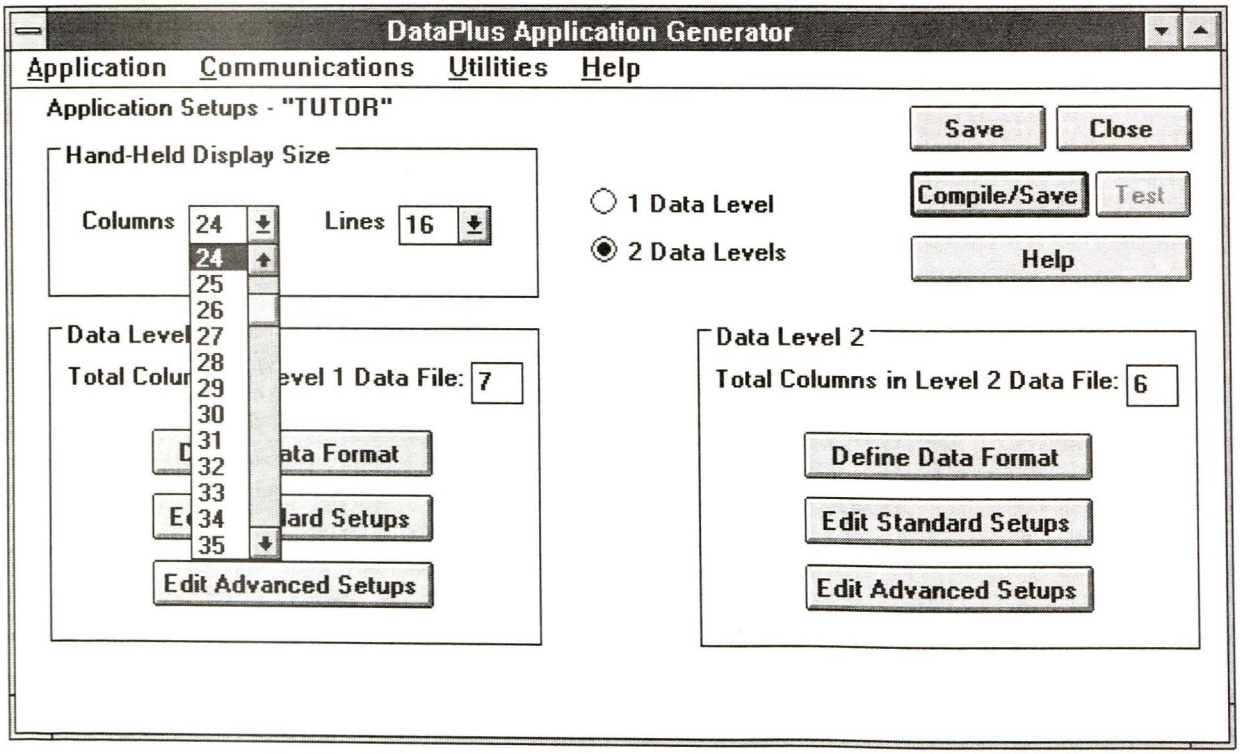
Once a new application is named, the main screen shown in figure 1 will appear. First, the hand-held display size is set to match the display for the particular hand-held for which the application is being generated.

Next, there can be either one or two Data Levels depending on the type of data being collected. For a "one-to-many" relationship, Data Level 1 is general (header) information that applies to Level 2 data. Level 2 data is a detailed breakdown of data that applies to the general information in Level 1. If general information is not required, one Data Level would be used. For this example, two Data Levels are selected. Total columns for each level are also set from the main screen.

After the number of columns is set for Data Level 1, the data format for Data Level 1 is defined by clicking on the Define Data Format button. The Data Format screen appears as in figure 2. The prompt can be up to 10 characters. The column size for character columns can be up to 30. Numeric columns can be as many as 15 including the decimal point. Once Data Level 1 settings are entered, the same procedure can be followed for Data Level 2. Editing can be done by using the Add, Insert, and Delete buttons.

Screen Define

The way data are displayed to the user on the hand-held can be modified using the Screen Define tab (fig. 3) from the Edit Standard or Advanced Setups button on the main screen. Line or Virtual screen types are available. A Line screen type format shows only one line of data at a time on the screen. The number of prompts and columns that can be viewed at one time is determined by the screen size. All information that will fit on the screen is displayed at one time. The rest of the data are displayed on subsequent screens. A Virtual screen type format presents


DataPlus Application Generator
Application
Communications
Utilities
Help
Save
Close
Compile/Save
Test
Help
Hand-Held Display Size
Data Level 1
Define Data Format
Edit Standard Setups
Edit Advanced Setups
Data Level 2
Define Data Format
Edit Standard Setups
Edit Advanced Setups
24
25
26
27
28
29
30
31
32
33
34
35

Application Setups - "TUTOR"

Columns 24

Lines 16

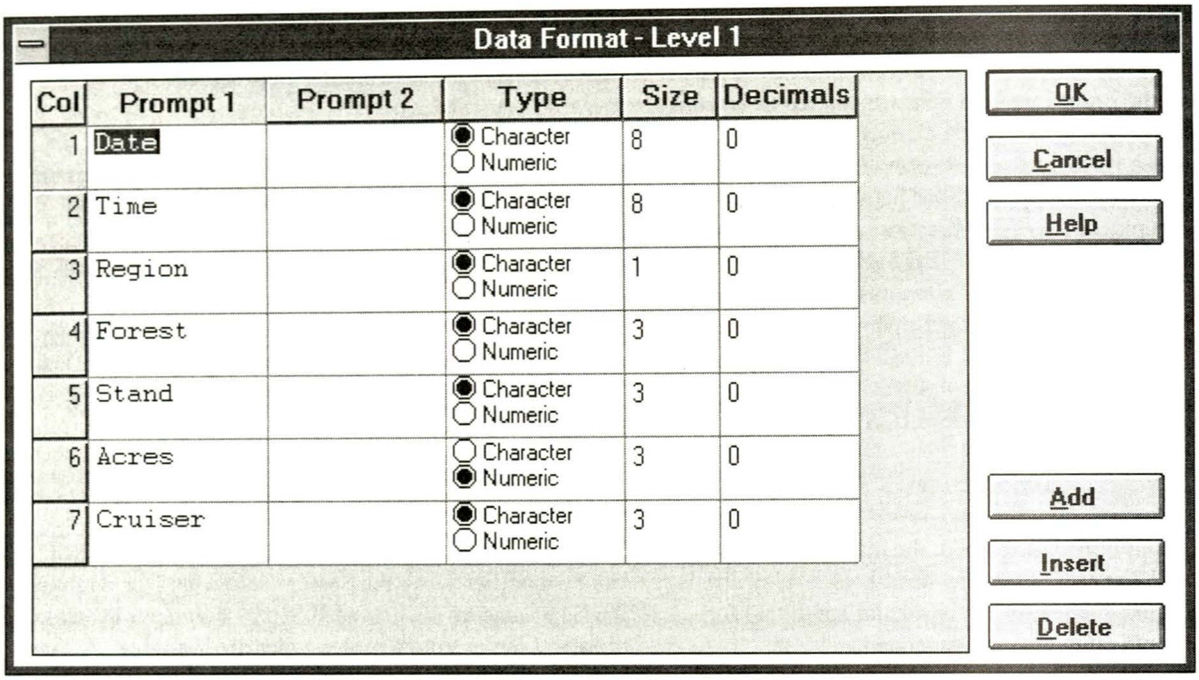
○ 1 Data Level

● 2 Data Levels

Total Columns in Level 1 Data File: 7

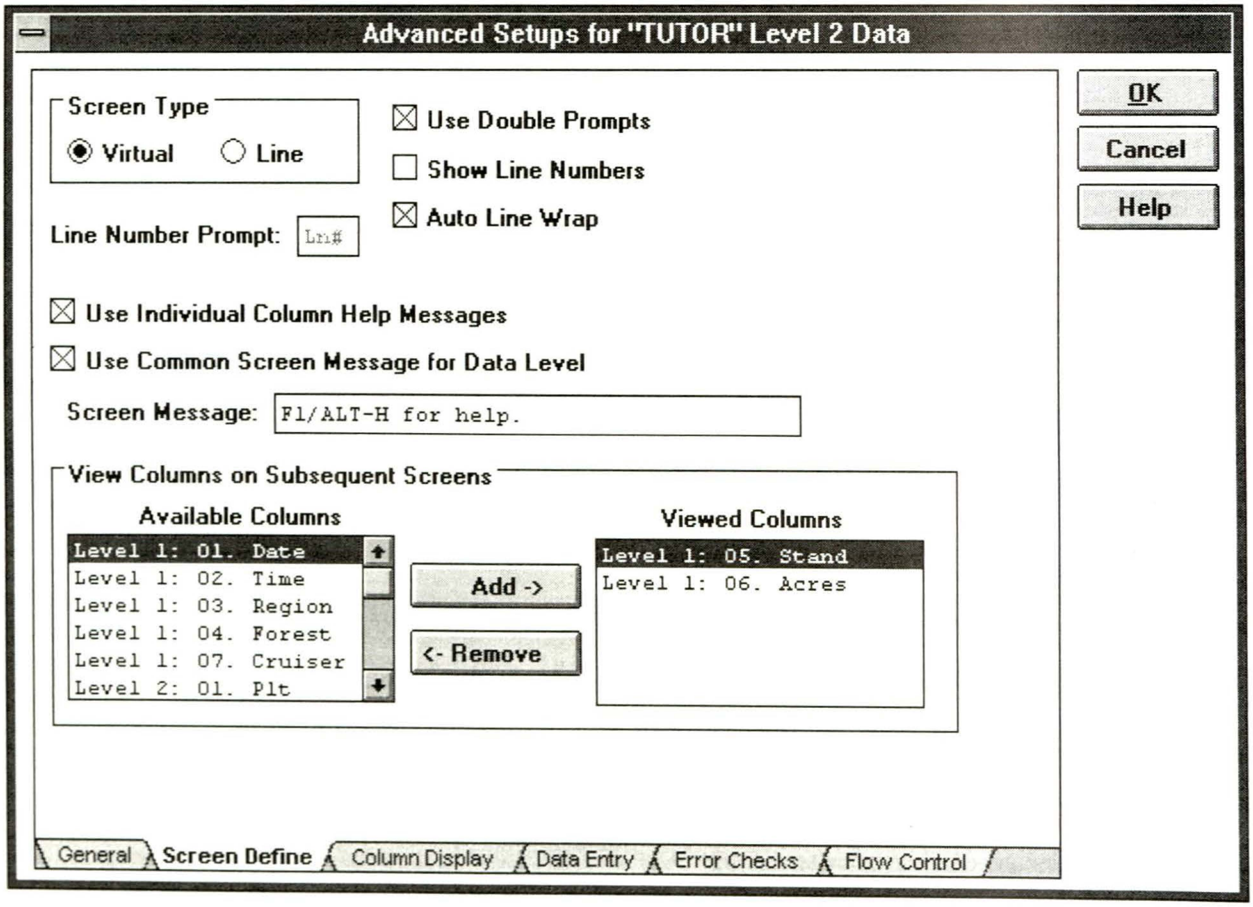
Total Columns in Level 2 Data File: 6

Figure 1.—*DataPlus For DOS allows the application to be customized for the hand-held computer display size.*


Data Format - Level 1
OK
Cancel
Help
Add
Insert
Delete

Col	Prompt 1	Prompt 2	Type	Size	Decimals
1	Date		● Character ○ Numeric	8	0
2	Time		● Character ○ Numeric	8	0
3	Region		● Character ○ Numeric	1	0
4	Forest		● Character ○ Numeric	3	0
5	Stand		● Character ○ Numeric	3	0
6	Acres		○ Character ● Numeric	3	0
7	Cruiser		● Character ○ Numeric	3	0

Figure 2.—*Data format is defined for header information using DataPlus For DOS.*


Advanced Setups for "TUTOR" Level 2 Data
OK
Cancel
Help
Add ->
<- Remove
General
Screen Define
Column Display
Data Entry
Error Checks
Flow Control

Screen Type: ● Virtual ○ Line

☒ Use Double Prompts

☐ Show Line Numbers

☒ Auto Line Wrap

Line Number Prompt: Ln#

☒ Use Individual Column Help Messages

☒ Use Common Screen Message for Data Level

Screen Message: F1/ALT-H for help.

View Columns on Subsequent Screens

Available Columns	Viewed Columns
Level 1: 01. Date	Level 1: 05. Stand
Level 1: 02. Time	Level 1: 06. Acres
Level 1: 03. Region	
Level 1: 04. Forest	
Level 1: 07. Cruiser	
Level 2: 01. Plt	

Figure 3.—*Using DataPlus For DOS, Screen Define options allow specific columns from previous screens to be viewed on subsequent screens.*

data in lines and columns. As many lines and columns that will fit on the screen at one time are presented together. The screen becomes a virtual window into the data that moves around with the cursor. Other Screen options that can be defined include:

1. Double lined prompts.
2. Auto line wrap. When enabled, the cursor automatically advances (wraps) to the next or previous line.
3. Show a particular column on subsequent screens.
4. Help messages can be defined for each column.
5. Columns can also be set to view only or be hidden to prevent user input.
6. Column data can be clipped to view a certain length with a slider window for data input.

Data Entry Types

To ease the task of entering data, DataPlus For DOS makes available two types of data entries that are defined for each column of each Data Level. Auto Data Entry Types are data entries that the hand-held enters automatically, and User Data Entry Types are the methods by which data can be entered into the hand-held. Standard and Advanced Auto Data Entry Types include:

1. Auto Copy. Data are copied forward from the cell above.
2. Auto Increment. Adds one to the value from the previous line in the same column.
3. Auto Date and Time. Reads the date and time from the hand-held's internal time clock.
4. Auto Line Number. Stores a line number for the current line.
5. Auto Random Number. Generates a random number with a definable limit.
6. Auto Increment Repeat. Data are incremented or decremented by a specific value.
7. Auto Preload. Default data are stored into the column.

User Data Entry Types are listed as follows:

1. Keyboard. Data are entered from hand-held keyboard.
2. Number in Character Field. Allows entering of numbers larger than 15 digits or if leading zeros are required.
3. Manually entered date and time information.
4. View Only. Used when the data should not be edited by the user.
5. Serial Port. DataPlus supports a full array of serial communication parameters to accommodate bar code scanners, electronic balances, GPS receivers, laser rangefinders, and water quality transmitters, to list a few.
6. Elapsed Time. Facilitates timed studies with 25 timers that can run simultaneously.
7. Fractional Time. Facilitates timed studies with separate columns for start and stop times.

Error Checking

The Error Check functions are used to check data as they are being entered into the hand-held. It is sometimes called data validation or data filtering. The two types of Error Check Types are Range and List File. Both have user override options.

Range Checks can be set for both numeric and character columns (fig. 4). The value entered by a user in a numeric column must be greater than or equal to a defined minimum value and less than or equal to the specified maximum value. For a character column, the entry string length must be greater than or equal to the specified value.

A standard List File Check is composed of one column of data used to compare against the user's input. This can be a List File of valid numbers or strings. There are two options for lists:

1. Sorted/Unsorted.
2. Translated/Not Translated.

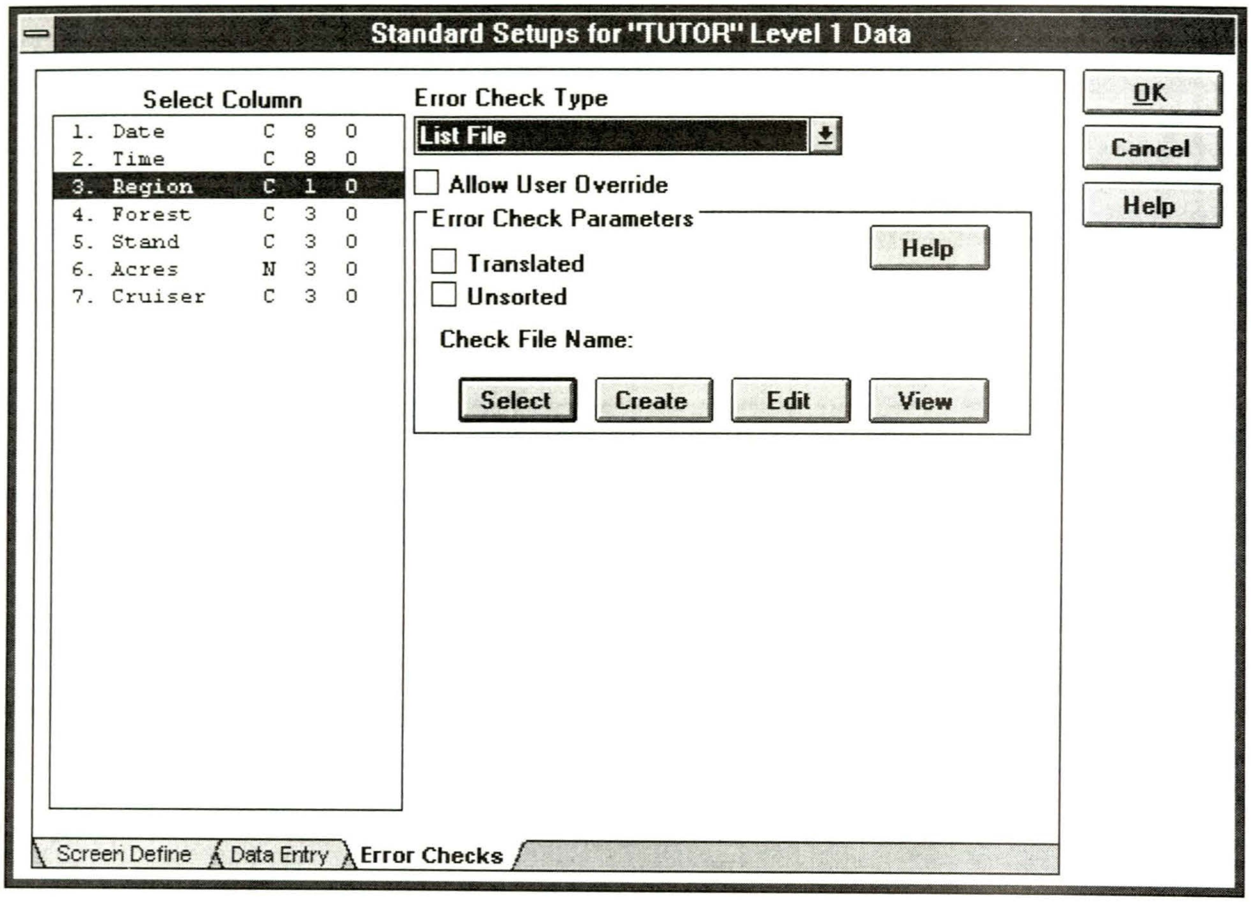
The default List type is Sorted in ascending, alphabetical, or numeric order. Unsorted is used if the list is to be grouped by category.

With hand-held computers, it is often much more efficient to key numbers instead of letters. Selecting a Translated list allows a code to be created which the computer translates into more meaningful data in the storage file. A Translated list can have three columns. The first column has the element used to check against the user input. The second column has the data that will actually be stored in the file. A description can be used in a third column for the code or abbreviation in the other columns.

The **F2** key on the hand-held may be pressed if the user desires to view the range or list check parameters. To be able to enter data outside the valid error checks, the Allow User Override box should be checked. If the user input data are out of the present range or list, a warning will alert the user that the data are outside the acceptable limits and entry must be confirmed with a **Y** or **N**. Otherwise, the user will not be allowed to input the data.

The Advanced error checks are relational checks—comparing input in one column based on data entered into a different column.

1. Range, Column Min Check Type—If the input value of data entered into a column falls within the absolute minimum and maximum, the input value must be greater than or equal to the data from the Source Column. For example, in log scaling operations, the small-end diameter of a log should be less than or equal to the large-end diameter of the same log. The large-end diameter column is checked that its diameter was greater than or equal to the small end diameter column.



Select Column

```
1. Date      C  8  0
2. Time      C  8  0
3. Region    C  1  0
4. Forest    C  3  0
5. Stand     C  3  0
6. Acres     N  3  0
7. Cruiser   C  3  0
```

Error Check Type: List File

☐ Allow User Override

Error Check Parameters

☐ Translated

☐ Unsorted

Check File Name:

Figure 4.—*Data integrity can be improved by using range and list error checking in DataPlus For DOS.*

2. Range, Column Max Check Type—If the input value of data entered into a column falls within the absolute minimum and maximum, then the input value must be less than or equal to the data from the Source Column. For example, in log scaling operations, the net weight of a load of logs should not exceed the gross weight. The net weight could be compared to the gross weight making sure it does not exceed the gross weight.
3. Range, Column Min/Column Max Check Type—If the value of data entered for a column falls within the absolute minimum and maximum, then the input value must be greater than or equal to the data value from the first Source Column and less than or equal to the data value from the second Source Column. For example, an error check could be set up to ensure that the mid-diameter column is greater in diameter than the small-end diameter column and less in diameter than the large-end diameter column.
4. Range File, Column Range Check Type—Data input to this column must fall within a pre-defined minimum, maximum range based on the data from another Source Column. For example, if a fish has a certain length range, its weight will be limited to a specific range. For each length, a different weight range is expected.
5. Range File, Two Column Range Check Type—Data entered into a column must fall within a pre-defined range based on the data from two other columns. For example, if a fish is in a certain length range and a certain girth range, it can be expected to fall in a certain weight range.

Flow Control

The Flow Control tab is used for defining movement within the data file based on data values.

1. List Jump Table. A Jump Table is based on data from a Source Column. The first column of the table is a Sorted List. If a data match is found for the Source Column, then a jump is performed to the column number value for the appropriate keystroke. For example, when cruising, a different height may be recorded based on the specific product. If the product is pulp, the height may be recorded as total height in feet, whereas for sawtimber, the height may be recorded as merchantable height based on the number of 8' or 16' logs. A jump table allows you to jump to

the appropriate height column for the specific product.

2. Range Jump Table. If the data fall within a certain range and a pre-defined key is pressed, the cursor will move to the column specified in the table.
3. Find First Empty. When moving from line to line, the cursor will stop when the first empty column is encountered up to a set limit. In forestry, this option is useful when entering all tree heights first and then going back to enter the diameters and defect data.
4. Relating Error Check Files and Jump Tables to Lists & Ranges. DataPlus also supports functions to relate data in pre-defined columns to a list or range. Based on the relate results, a specific check file or jump table can be used. For example, each region in the USDA Forest Service has its own list of national forests. A Related List is made for the Forest column. The Forest column is related to the Region column. When the Region column has Region 1 entered in it, only national forests for that region are accepted or viewed.

DATAPLUS HAND-HELD SOFTWARE

After the DataPlus application is installed on the DOS hand-held, the user is provided with a menu system for collecting data and accessing hand-held utilities. The Collect Data menu option allows the user to enter field data as specified in the Applications Generator. DataPlus For DOS supports keystroke functions to speed cursor movement and navigation through data, and to provide run time functions. Erase Data deletes the data stored in the current application.

The hand-held transmits collected data to the PC and receives applications sent from the PC with the Communications menu option. It facilitates direct or modem connections. It supports standard communication protocol parameters.

The Applications option allows the user to select the desired DataPlus application. DataPlus can accommodate up to 256 applications.

The Utilities and Setup options allow for setting the clock, checking memory and drives, deleting applications, changing the display sizes for columns and rows, and setting passwords. A two-level password security system is available for erasing and data.

DATAPLUS HOST MODE

DataPlus Host is a program used specifically for communicating with hand-held computers to retrieve data. Typically, data are gathered in the field using DataPlus For DOS on a hand-held, then communicated to a "host" PC running the DataPlus Host program. DataPlus Host takes care of the transfer and organization of the communicated data on the disk drive of the host computer.

DataPlus Host is a "stand-alone" program, meaning that it is a separate Windows program and not an internal part of the DataPlus Application Generator. This isolation between programs permits DataPlus Host to be used without having to depend on the DataPlus Application Generator; therefore, DataPlus Host may be receiving data from a remote hand-held at the same time as applications are being created or modified in the DataPlus Application Generator. An additional benefit of this independence is the relatively small size of the DataPlus Host program compared with the DataPlus Application Generator. This smaller size allows for more Windows applications to be open simultaneously when only DataPlus Host is required to be functioning. DataPlus Host will continue to monitor direct or modem connections at all times even while other Windows programs are running. It may therefore be "iconified" so it will not take up display space on your Windows screen, and still connect with remote hand-helds.

When a remote hand-held running DataPlus For DOS successfully connects with DataPlus Host to transfer its collected data, an automated log in procedure takes place. This procedure requires no user interaction because it is a conversation between the hand-held and the host PC. The hand-held informs DataPlus Host of the hand-held's unit ID and current application name. DataPlus Host then organizes the received data from the hand-held into the appropriate location on the hard drive of the host PC.

DATAPLUS PROFESSIONAL OVERVIEW

DataPlus Professional is an applications generator and program editor for DOS hand-held computers that is scheduled for release during fourth quarter of 1998. DataPlus Pro has everything that DataPlus For DOS offers but adds features that software developers and information systems managers will appreciate and have requested. Users can choose which version is right for their application.

What's New in DataPlus Pro?

DataPlus Pro consists of four separate programs including hand-held data collection software, a Windows 95 or NT compatible applications generator, the DataPlus Host, communications software package, and an additional program editor called DPCedit.

DataPlus Pro is compatible with most DOS-based IBM compatible hand-held computers. Supported display sizes range from 6 to 25 lines and from 20 to 80 columns. Two hand-held versions are included: one is for use with a 286 or greater processor and the other version is for 8088 or greater processors. Minimum hand-held hardware configurations include DOS 3.1 or greater, 640K of free RAM, and 500K of free disk space. Minimum hardware configurations for the PC include Windows 95 or NT, SVGA Graphics, 8 Meg of RAM, and 4 Meg of free hard disk space.

DataPlus Pro supports many new features to customize advanced applications as shown in figure 5. The major enhancements are:

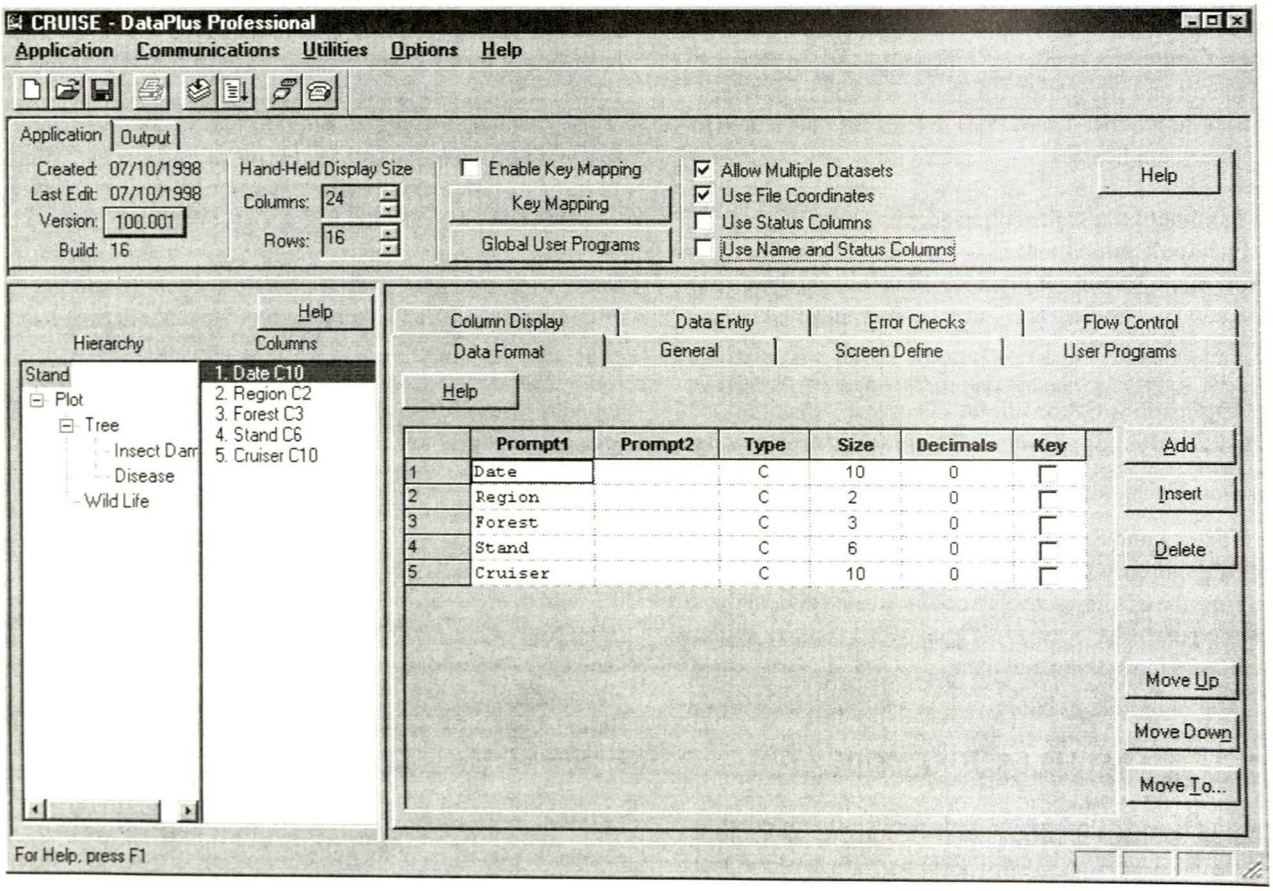
1. Provides for up to four data levels with up to nine branches from each file and up to 26 independent sets of data for each application.
2. Facilitates the use of custom user programs to implement features not present such as calculations, report printing, data flow control, etc.
3. Expanded data entry types, constant data displays, error checks, missing data checks, and data formats.
4. Allows the order in which data are entered to be controlled according to the data already entered.
5. Extended BIOS support for power management.
6. Remap keys on hand-helds with limited keyboards.
7. Windows 95 and NT Compatible.
8. Improved interface for easier navigation to any part of the configuration process including toolbars and DataPlus Pro buttons.
9. Application version control for coordination of PC and hand-held application versions.

Custom User Programs

DataPlus Pro incorporates a program editor that greatly extends the flexibility of the product. This allows for advanced, customized features that include calculations, error checking, data flow control, report printing from the hand-held, and power management.

The programs are written in a "C" like programming language called DPC. A sample program is shown in figure 6. The code is compiled before loading into the hand-held to increase its execution speed in the field. The 11 types of user programs are:

1. Global level user programs. Accessed any time data are being collected within the application.
2. File level user programs. Accessed only while collecting data for the file the program is associated with.



CRUISE - DataPlus Professional
Application
Communications
Utilities
Options
Help
Application
Output
Help
Key Mapping
Global User Programs
Help
Column Display
Data Entry
Error Checks
Flow Control
Data Format
General
Screen Define
User Programs
Help
Add
Insert
Delete
Move Up
Move Down
Move To...
For Help, press F1

Created: 07/10/1998
Last Edit: 07/10/1998
Version: 100.001
Build: 16

Hand-Held Display Size
Columns: 24
Rows: 16

☐ Enable Key Mapping

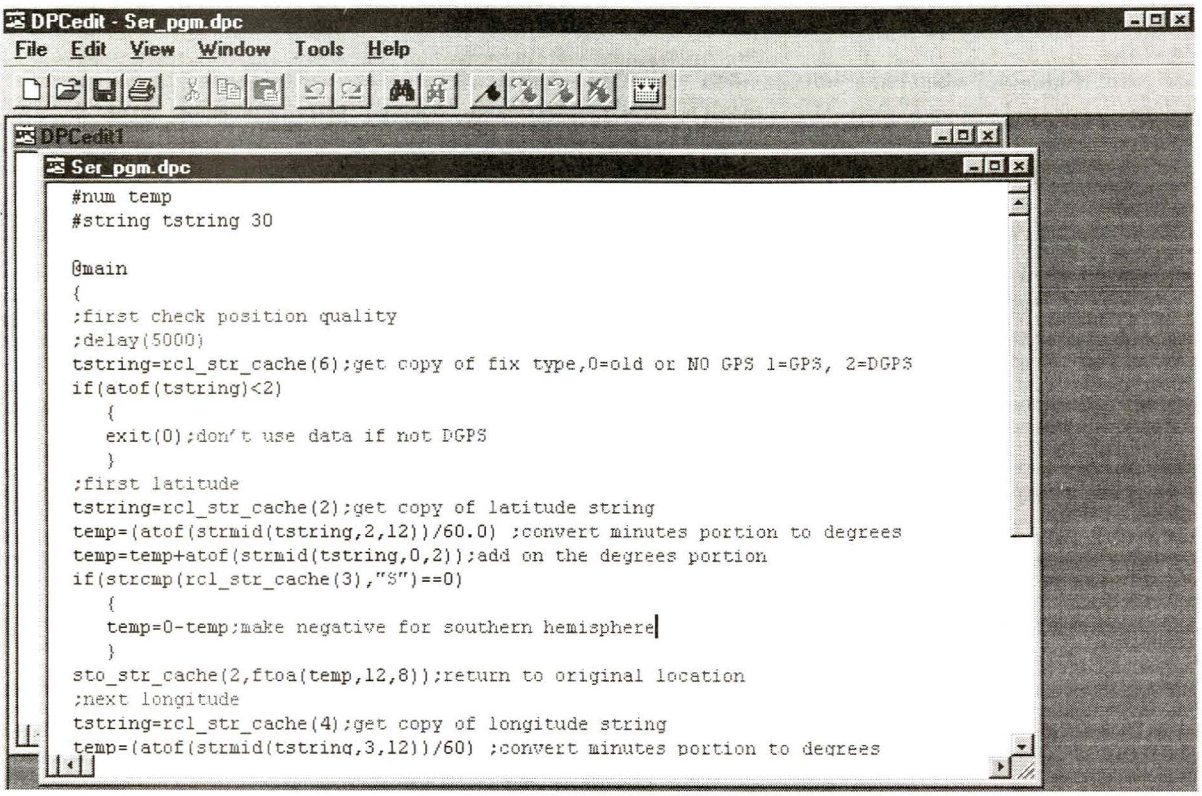
☑ Allow Multiple Datasets
☑ Use File Coordinates
☐ Use Status Columns
☐ Use Name and Status Columns

Hierarchy
Stand
⊟ Plot
  ⊟ Tree
    Insect Dam
    Disease
  Wild Life

Columns
1. Date C10
2. Region C2
3. Forest C3
4. Stand C6
5. Cruiser C10

	Prompt1	Prompt2	Type	Size	Decimals	Key
1	Date		C	10	0	☐
2	Region		C	2	0	☐
3	Forest		C	3	0	☐
4	Stand		C	6	0	☐
5	Cruiser		C	10	0	☐

Figure 5.—*DataPlus Pro offers features for advanced customization of applications.*



```
#num temp
#string tstring 30

@main
{
;first check position quality
;delay(5000)
tstring=rcl_str_cache(6);get copy of fix type,0=old or NO GPS 1=GPS, 2=DGPS
if(atof(tstring)<2)
   {
   exit(0);don't use data if not DGPS
   }
;first latitude
tstring=rcl_str_cache(2);get copy of latitude string
temp=(atof(strmid(tstring,2,12))/60.0) ;convert minutes portion to degrees
temp=temp+atof(strmid(tstring,0,2));add on the degrees portion
if(strcmp(rcl_str_cache(3),"S")==0)
   {
   temp=0-temp;make negative for southern hemisphere
   }
sto_str_cache(2,ftoa(temp,12,8));return to original location
;next longitude
tstring=rcl_str_cache(4);get copy of longitude string
temp=(atof(strmid(tstring,3,12))/60) ;convert minutes portion to degrees
```

Figure 6.—*With the built-in program editor in DataPlus Pro, the user can write custom programs for calculations, report printing, and data flow control.*

3. Data level entry user program. Runs when the file is first opened for data collection.
4. Data level advance user programs. Runs when advancing to child (a branch) data files.
5. Data level retreat user programs. Runs when returning to the parent data file.
6. Sibling jump user programs. Runs when jumping to a sibling data file (a data file of a different branch from the same parent data file).
7. Column change user programs. Runs when moving from column to column within the same data file.
8. Line change user programs. Runs when moving from line to line within the same data file.
9. Data entry user programs. There can be a separate data entry program for each column in each file. They can run before user entry, after user entry, or instead of user entry.
10. Error check user programs. There can be a separate error check program for each column in each file. They can run before standard error checks, after standard error checks, or instead of standard error checks.
11. Serial port data entry user programs. The incoming data can be manipulated or validated before using.

Power Management

Any field computer is effective only as long as the battery lasts. Hand-helds with extended BIOS capabilities can take advantage of the more robust power management available in DataPlus Pro. Interrupt calls are configured for the specific hand-held for power-saving features that are called as needed for CPU idle, return from CPU idle, and turning COM ports on and off. Up to two interrupts can be called for each port. This allows COM ports to be turned on and off and allows light pen power to be turned on and off when the serial ports are opened and closed. Two external programs or system calls can be executed when DataPlus Pro first starts and up to two when exiting the program. In addition to power-saving features, the external programs can be used for other functions, such as DOS "MODE" calls or time out functions.

Missing Data Checks

DataPlus Pro contains expanded missing data checks. Missing data checks can be enabled or disabled to check for required data in each file. If the missing data check finds a column with required data not entered, an audible warning is sounded and the cursor moves to that column for data entry. The following options are available:

1. Check the current data line when advancing to the next data line.
2. Check the current data line when either advancing to the next data line or backing up to the previous data line.
3. Check the current data line before advancing to the next data level.
4. Check the current data line before jumping to a sibling data level.
5. Check all lines in the current data file before retreating to the parent data level using the F4 key.
6. Check all lines in the current data file when the ESC key is pressed to retreat to the parent data level.

COMPATIBLE DOS HAND-HELD FIELD COMPUTERS

Both versions of DataPlus have been tested to run on these DOS hand-held computers:

1. Juniper Systems Pro2000
2. DAP PC9000, PC9500, & PC9800
3. Husky FS/2, FS/3, & FS/GS
4. Hewlett Packard HP200LX
5. Paravant RHC-44E
6. CMT PC-5L

CONCLUSION

Both DataPlus versions were developed by Electronic Data Solutions in Jerome, Idaho. Electronic Data Solutions has specialized in catering to the data recording applications in natural resource markets for the last 12 years. Since DataPlus For DOS and DataPlus Pro are economically priced at $249 and $595, respectively, they give all data collection specialists a revolutionary new software tool.

For more information and to download demonstration software, contact us at our web site: www.elecdata.com.

DataPlus is a recognized trademark of Electronic Data Solutions. All other trademarks are registered or recognized trademarks of their respective owners.

ACKNOWLEDGMENT

The following people reviewed this manuscript: Mike Duppong, Programmer, Electronic Data Solutions, Jerome, ID, USA; and Pam O'Dell, Office Manager, Electronic Data Solutions, Jerome, ID, USA.

Eucalyptus Forest Information System for the Portuguese Pulp and Paper Industry

Luis Fonseca, Rita Crespo, Henk Feith, José Luis Carvalho, António Macedo, and João Pedro Pina

Abstract.—To support the management of the Portuguese eucalyptus forest, the Association of Portuguese Pulp and Paper Industries (CELPA) decided to develop a Eucalyptus Forest Information System (EFIS). The specific goals of the EFIS are: characterization and development of the eucalyptus forest over time; planning of successive national eucalyptus forest inventories; estimation of sustainable eucalyptus pulpwood yield; development of growth and yield models; and monitoring of mean and current annual increment. This paper gives a concise image of the Portuguese eucalyptus forest and explains the structure of the system and the expected results.

THE PORTUGUESE HARDWOOD PULP FOREST AND PULP AND PAPER INDUSTRY

The Portuguese Hardwood Pulp Forest

The Portuguese hardwood pulp forest area is composed of various eucalyptus species, of which *Eucalyptus globulus* Labill. clearly predominates, and covers about 590 thousand ha of pure and mixed stands (CELPA 1996). Most of this area is located in the coastal area due to its favorable edapho-climatic growth conditions. About 30 percent of the eucalyptus area is owned or managed by the pulp industry; the rest belongs to mostly small private forest owners. According to the Eucalyptus Forest Inventory of 1997, the current annual wood production in 1996 was estimated to be 4.8 million m^3 inside bark. However, the harvestable volume inside bark in 1997 was estimated to be 3.5 million m^3 due to the unbalanced age distribution of the stands; therefore standing volume is assumed to increase during the coming years (CELPA 1997).

The stands are managed in a treatment-intensive coppice system with an average cutting age between 8 and 12 years. Most stands are replanted after three cutting cycles. The mean annual increment (MAI) at cutting age oscillates between 5 and 20 m^3 per hectare inside bark for most stands, with a national average of 10 m^3 per hectare per year. Recent studies indicate an optimal cutting age of 12 instead of the most commonly used 10-year cutting cycle (Ribeiro *et al.* 1997). Governmental forest policy limits a further expansion of the eucalyptus area on a national level, promoting the trading off of eucalyptus stands in areas of poor productivity for new areas in highly productive regions (DGF 1998).

The first steps have been taken to define and control sustainable yield for the eucalyptus area, both at a national scale (DGF 1998) and at the enterprise level, and some of the pulp enterprises are working towards the certification of the forest management and its products.

The Portuguese Pulp And Paper Industry

The Portuguese pulp industry is composed of six companies with a total of seven mills; two of these mills also consume softwood. The total hardwood consumption in 1997 was about 4.5 millions m^3, which was used to produce almost 1.4 million tonnes of bleached pulp. Most of the pulp is produced using the sulphate (kraft) process; less than 1 percent is produced with the sulphite method. Total pulp production has increased by about 20 percent in the last 10 years. Thirty percent of the pulp production is used directly in an integrated pulp/paper production system. The national market consumes another 5 percent, and the remainder is exported mainly to European Community countries. A total of 100 thousand tonnes of pulp is imported (CELPA 1997).

The Portuguese paper and board industry consumes 410 thousand tonnes of hardwood pulp, 305 thousand tonnes of softwood pulp and 320 thousand tonnes of recovered paper, annually producing 1.1 million tonnes of paper and board, of which 50 percent is graphic paper. The total Portuguese pulp production is about 4.7 percent of European production and 0.9 percent of the world pulp production. About one-third of the production is consumed by the internal market, and the rest is exported (CELPA 1997).

Fonseca and Crespo, Head of the Forest Inventory Working Group and GIS Specialist, respectively; CELPA, Associação da Indústria Papeleira, Lisbon, Portugal; Feith, Head of the Forest Inventory Department of Silvicaima Sociedade Silvícola Caima Lda, Constância, Portugal; Carvalho, Forest Manager of Portucel Florestal, Torres Novas, Portugal; Macedo, Head of the Forest Planning and Management Department of Soporcel SA, Lisboa, Portugal; Pina, Head of the Forest Planning Department of Stora Celbi, Figueira da Foz, Portugal.

GOALS OF THE SYSTEM

Introduction

The Portuguese pulp and paper industry uses mainly eucalyptus wood as its raw material. To be able to estimate the availability of eucalyptus pulpwood on the national market, CELPA has implemented successive national eucalyptus forest inventories on a 5-year cycle since 1986. These inventories were preceded by aerial photograph coverage, which was used to estimate the area of eucalyptus forest.

After three inventory campaigns, it was decided to create a forest information system that should be able to integrate not only the existing information from the aerial photographs and the inventories, but also other sources of information concerning growth and presence of eucalyptus in Portugal and other related data. This forest information system would also perform analyses that were previously not feasible. The main goal of this Eucalyptus Forest Information System (EFIS) is the production of information required by the industry for their strategic planning concerning the optimal forest area, and its extent and distribution, that balances national wood production and consumption, minimizing the need of wood importation.

Goals

The EFIS will be used to archive, integrate, and manage all the available and obtainable information on eucalyptus forests in Portugal using georeferenced data together with other types of data in a digital format. Once it is fully operational, the system will produce concise information, it will have the ability to update systematically existing data, and it will allow a rapid response to information requests.

The specific goals of the EFIS are to support the characterization and distribution of the Portuguese eucalyptus forest; monitoring of the development of the Portuguese eucalyptus forest over time; planning and organization of the successive national eucalyptus forest inventories; determination of actual standing volume; estimation of sustainable eucalyptus pulpwood yield at short, middle and long term; development of general and regional growth and yield models for eucalyptus stands; and monitoring of mean and current annual increment in the different types of eucalyptus forests.

DESCRIPTION OF THE SYSTEM

Operational Environment

The team that runs the system is composed of three operators: a GIS specialist, a Forest Inventory specialist, and a technical operator. The system uses a Workstation Sun Ultra 1 Model 170 and three Pentium PC's, a printer, an A0 plotter, and an A0 digitizing table. The computers are linked through a network in a Unix/Windows95 environment. The EFIS includes a GIS environment, equipped with ESRI software such as Arc/Info, ArcPress, and ArcView. The database is developed under Microsoft Access.

Functional Components

The first component of the EFIS is the collection and input of existing data from three different sources: CELPA supplies information regarding national forest inventories, aerial photography data and orthorectified digital aerial photographs, a national eucalyptus forest map, a cartographic base map of Portugal rasterized from a 1:250000 map, and geographic locations of pulp and paper mills and operational centers of forest fire control; associated forest companies supply data from their Continuous Forest Inventories (CFI), digital cartographic information, and data from silvicultural field trials; external sources like national cartography and forest services, universities, and research institutes supply cartographic data, administrative data, thematic data, and information from silvicultural field trials.

The second component is the organization and management of the information. The existing data are used to construct spatial or non-spatial databases that allow queries and systematic data integration, manipulation, and analysis. The cartographic information (spatial databases) is stored in a GIS environment for spatial analyses such as overlay of the different inventory themes.

The third component is the supply of existing information and production of new information meeting the needs of both industry and forest managers. The EFIS is used as an information center of forest data for the associated forest and pulp companies and, to a smaller extent, for the public in general.

Results

The system has been in a construction phase since January of 1997. At the moment, the photointerpreted data and field plots collected for the Eucalyptus Forest Inventory (EFI) in 1996 have been entered into the system and the constructed database is already fully operational. These results were described and analyzed in a thorough statistical study to characterize and map the eucalyptus stands. To support and complement this study with a spatial interpretation of the data, thematic maps regarding distribution and occupational rate of mixed and pure stands, age, volume, MAI, harvesting, and several other thematic maps were produced by the system. A geostatistical approach concerning spatial distribution of age and site index classes has proven useful in identifying homogeneous forest regions based on these variables. It is also a promising methodology whose analyses complement the inventory results.

The aerial photography data are composed of 4,889 photographs that cover the whole country. This analogic data set is being converted to digital orthophotos. Pixel resolution is approximately 1 m, providing a useful tool for cartographic applications. This database provides a quick overview of the photography/orthophoto characteristics and, as it is georeferenced, allows geographic queries as well as visualization of the position of the records.

The digital orthophotos are used in the GIS environment as an updated land-use document where it is possible to position the georeferenced inventory plots. Presently these images are used to map forest properties and are proving to be a powerful and efficient mapping method. They are also the cartographic base for producing the national eucalyptus forest map. This map is still being produced and, at this primary phase covers the center of Portugal where the eucalyptus is preferentially distributed. More precise information derived from this map will be used to compare with the last forest inventory, and the results will be used to help plan and support future inventories.

The properties explored by the associated forest companies from CELPA are stored in the EFIS where they are used as an important layer on the Forest Fire Fighting Map, together with a cartographic base map. This Forest Fire Fighting Map was printed at a 1:250000 scale, and a complementary digital format was produced for forest fire fighting GIS applications. This map will be updated and improved every year.

All these data are constantly being updated and subjected to further manipulation as required.

Future Developments

In the near future, CELPA plans to enter all existing data concerning previous inventory campaigns. These data will be georeferenced to be able to integrate them in the EFIS and perform an analysis of the development of the eucalyptus area, both in extent, and in growth, at regional and local levels. It is also interesting to study the actual eucalyptus area and its relation to the geographic position of pulp and paper mills and the road network.

The geographical analyses of the results of the last inventory will lead to the identification of the areas with major potential production capacity of *Eucalyptus globulus* Labill. within Portugal, as well as the areas with marginal potential production capacities. Combining these data with geostatistic tools, it is possible to produce an optimal eucalyptus forest distribution map that satisfies the industry wood requirements. Once accessible for associated forest companies, the system can be used for the selection of potential expansion areas. This analysis will have to reflect the existing legislation as well as local and regional management plans that supervise the forest and natural resources exploitation. The inventory results, the national eucalyptus forest map, the area and inventory results from the properties managed by the associated forest companies, and decision support models will act together to help plan future inventory campaigns toward better forest management for production, sustainability, and protection.

The system will continually archive new data needed for future analyses such as protected areas, forestry perimeters, inventory data from other institutions, meteorological data, environmental data, burned areas, digital terrain models, and road networks.

For forest fire control, there is a need to develop an application that involves GIS tools to georeference forest burned areas and to better manage the forest fire control resources. This application involves the mapping of existing water bodies, planning the distribution of water deposits, mapping helicopter bases from other entities, integrating maps of forest fire index risk, and mapping forest fire surveillance towers. It is essential to monitor the affected areas and study the fire distribution evolution on a multitemporal basis to determine fire tendencies or preferential areas.

Integration of satellite data in the EFIS can be a valuable and economically interesting source of information. As in the past, CELPA will be attentive to the development of new and sophisticated technology and methodologies that might improve EFIS functionality and results.

ACKNOWLEDGMENTS

The following people reviewed this manuscript: David Reed, School of Forestry and Wood Products, Michigan Technological University, Houghton, Michigan, USA, and José Miguel Cardoso Pereira, Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Lisbon, Portugal.

LITERATURE CITED

CELPA. 1996. Inventário Florestal do Eucalipto 1995/1996. Relatório Sucinto. CELPA. 20 p.

CELPA. 1997. Annual statistics of the Portuguese paper industry. CELPA. 69 p.

DGF. 1998. Plano de Desenvolvimento Sustentável da Floresta Portuguesa. Base para a Discussão Pública. Direcção-Geral das Florestas. 89 p.

Ribeiro, F.; Soares, P.; Tomé, M.; Cadete, D.; Pina, J.P. 1997. Determination of initial stand density that optimizes the system production of *Eucalyptus globulus* Labill. in Portugal. In: Proceedings of the IUFRO conference on silviculture and improvement of eucalyptus; 1997; Colombo, Brasil; Embrapa, CNPF Vol. 3: 125-129.

Defining and Predicting Urban-Wildland Interface Zones Using a GIS-Based Model

Lawrence R. Gering, Angel V. Chun, and Steve Anderson

Abstract.—Resource managers are beginning to experience a deluge of management conflicts as urban population centers expand into formerly wildland settings. Fire suppression, recreational, watershed management, and traditional forest management practices are activities that have become contentious in many locales. A better understanding of the interface zone between these two types of land is important if managers are to successfully maintain the values of such lands. A pragmatic model for defining the urban-wildland interface for LeFlore County, Oklahoma, was developed, allowing identification of these transitional zones. Census data were used to obtain information on housing densities, population densities, and other social and cultural activities. LandSat MSS images provided a description of the current land cover and land use of the study area. Additional data (such as digital soil maps) were processed and added to the GIS structure. On-site ground truthing was also conducted.

THE URBAN-WILDLAND INTERFACE

Since the beginning of colonization of North America in the 17th century, communities have been created by clearing and developing wildlands. Every farm, town, and metropolitan area was originally carved from forested areas or other wild landscapes. Early settlers considered these undeveloped lands as either a barrier to be conquered or as a major source of raw materials for commodity production. Today, people often view these areas with different attitudes and motivations. The attraction of rural landscapes and the appeal of a home on a large lot often influence people to move beyond established cities. This has resulted in conflicts involving urban development and preservation or use of pre-existing wildlands.

The urban-wildland interface of today differs from earlier urban encroachment into wildland settings. In the early part of this century, great numbers of people left their farms and moved to cities as industrial jobs became available. After World War II, people in urban areas began to migrate back toward rural areas, creating vast suburbs around cities. By the late 1950's an "urban/rural fringe" surrounded many cities, with manufacturing enterprises and suburban development merging with rural communities. It has become increasingly important to properly manage the natural resources in the transitional zones between urban areas and areas traditionally considered wildlands; these zones are often referred to as urban-wildland interfaces.

These interfaces may be better understood by discussing the competing uses for urban fringe lands and the principal motivations of landowners. This also provides insight into the complexity of the problem and why the management of these areas is of interest to natural resource managers. Lee (1984) suggests that the interface can be characterized as an ecological condition in which human activities and artifacts interact with natural objects in a wildland ecosystem. This is illustrated by the urban-wildland interface fire hazard problem: the interface is characterized by the rapid transfer of heat from wildland fuels to fuels found in residential structures, or vice versa. Another adverse and significant problem involves the use of these areas for recreation: for example, the impact of all-terrain vehicles on the vegetation within these sensitive areas. Other potential problems occur when people move to these areas and bring along domestic animals that may impact the existing natural wildlife population.

The interface may be accurately delineated by distinguishing between its geographic, social, and ecological components. From the aesthetic perspective, the interface is a wide and sometimes nebulous boundary distinguished, for the most part, by the presence or absence of trees. From a jurisdictional perspective, the interface is sometimes thought of as either the boundary between public and private land or the point where parcel size begins to change from relatively small to relatively large lots. Where structures appear on the landscape, the interface

---

Associate Professor of Forestry, Oklahoma State University, Stillwater, OK, USA; Director of Forest Management, Belize Forest Service, Dangriga Town, Belize; President, Forest History Society, Durham, NC, USA, respectively.

may be defined by a line drawn between the built and non-built environment. Finally, using physical and biological growth criteria, the interface may resemble a soil map, where highly productive lands are distinguished from less productive lands. The union of all three components represents a situation in which values are assigned to particular linkages between human activities and natural ecosystems in an area where residential development is located within or near a forest (Chun 1996).

The interface between urban and rural settings represents a paradox with the urban and rural perspectives having some characteristics in common as well as points of conflict. Many city dwellers depend heavily on rural landscapes for recreational activities. Suburbanites or people living in the interfaces may argue that the presence of agricultural operations negatively influences their living space. For example, prescribed burning, a recognized forest and wildlife habitat management tool, has a strong negative connotation for many city dwellers. Urban noise,wildlife, domestic and farm odors, dust control, and concerns about non-point-source pollution and waste disposal are other issues. Thus, a tension zone is created between urban and rural settings. Resource managers are now beginning to experience a deluge of conflicts involving such practices as fire suppression, recreational overuse, watershed management, and traditional forest management. A better understanding of this urban-wildland interface is of utmost importance if managers are to successfully understand and maintain the values of these lands.

If natural resource managers are to be able to effectively manage urban-wildland interfaces, they must first need to be able to identify these zones. Numerous attributes such as vegetative cover, land use, housing density, housing location, population density, land ownership status, surface water features, topography, and other characteristics that could potentially affect the resources or the resource users must be considered. To accomplish such an undertaking, attributes must be referenced by a common denominator. One factor that each of these attributes has in common is a specific spatial location; therefore, they can all be referenced by their geographic location.

STRATEGY FOR DEVELOPING THE MODEL

A common and reasonable understanding of what is meant by the urban-wildland interface must include the development of a set of pertinent criteria that suggests an implicit and usable definition of the urban-wildland interface. However, the actual criteria may differ. A criterion is a category of conditions or processes by which the urban-wildland interface may be assessed. It is characterized by a set of related indicators that are monitored periodically to assess change. A factor is a measure of an aspect of the criterion. It is a quantitative or qualitative variable that can be measured or described and that, when observed periodically, demonstrates trends. No single criterion or factor defines the urban-wildland interface; they must be looked at as a set of interrelated characteristics within a social and environmental context. For this project it was proposed that urban-wildland interface be defined or characterized by a set of criteria and related factors. The criteria selected for this study were:

1. Physical and biological criteria define the interfaces in terms of what actually constitutes the zone. This refers not only to flora and fauna but also to physical factors such as soil types. Vegetation, taken as the composite of the whole assemblage of plants growing in an area, responds to physical environmental factors such as climate, soils, hydrology, and elevation. Therefore, natural vegetation provides a good summary of the physical properties of any location.

2. Jurisdictional criteria can view the interface as either the boundary between different land ownerships or whether the areas lie within the boundaries of minor civil divisions (such as town boundary limits). This includes both private and public ownership.

3. Economic criteria can be measured by looking at median income levels per household. Increased population and real personal income have been linked to urbanization of forested areas (Alig and Healy 1987).

4. Development criteria can be measured by the presence or absence of humanmade structures on the landscape. People often make use of wildland environments for their second homes and for cultural development. The importance and validity of this criterion is increasing as fire and recreation-related management problems arise because of this activity.

THE STUDY

The purpose of this project was to develop a pragmatic model for defining the urban-wildland interface through an identification and evaluation of potential data sources and variables representing land-use/land-cover, economic, and social factors. Several limitations concerning the overall scope of this project and specific data analyses were necessary. These required that the development and implementation of the model be restricted to one county in Oklahoma and that data would be obtained from information derived from census studies, satellite imagery, other digital data sources, and field work (Chun 1996).

The study area for this work was LeFlore County, located in the southeastern part of Oklahoma. The county includes 4,097 km^2 (1,582 square miles), mainly in the Arkansas River Valley and the Ouachita Mountains physiographic sections. Topography differences range from the nearly level floodplains of the Arkansas, Poteau, and Kiamichi Rivers to the steep mountainous areas in the southern part of the county. Many low ridges are adjacent to the rolling and undulating areas of the northern part of the county. The total population is 46,300 residents, and urban areas include Poteau (8,200 residents), Pocola (4,600), Heavener (2,800), Spiro (2,500) and Arkoma (2,300). Fort Smith, Arkansas (55,000) lies east just across the Oklahoma/Arkansas state line and has a significant economic and social impact on LeFlore County (Oklahoma Department of Commerce 1993). Historically, the region consisted of small subsistence farms with cotton and corn as the major crops. Recently, the trend in farming has moved towards livestock farming. Many of the upland areas are now pasture with cultivation limited to bottomland areas.

LeFlore County was chosen because it has a substantial economy based on natural resources. Many of the residents are part-time ranchers. Woodland industries use hardwood and pine timber, and several sawmills and charcoal plants operate in the southern part of the county. The county also includes part of the Ouachita National Forest and the Winding Stairs Mountain National Recreation and Wilderness Area.

DATA

The primary sources of data for this project were remotely sensed land-cover data combined with data from the US Census Bureau's TIGER/Line files. For the land-cover/land-use data layer, recent (March 1992) LandSat Multispectral Scanner images were obtained; use of MSS data was a constraint based on the available budget for the project. The images were registered to ground coordinates and classified to produce land-use/land-cover classes. Eight categories were created: urban, cropland, rangeland, pasture, pine, hardwood, wetlands, and water. Ground truthing was conducted, and the classification accuracy was considered satisfactory. Additional data included a file containing digitized soil maps, which was obtained from the Oklahoma State University Department of Geography.

Land-cover variables cannot reveal economic and social information. However, these data sets can be obtained using TIGER/line files. TIGER is an acronym for Topologically Integrated Geographic Encoding and Referencing system. It allows for the creation and maintenance of a digital GIS database using data from the 1990 Census. It provides complete coverage of the United States including line features such as roads and railroads, landmark features such as schools and churches, and polygon features such as census statistical data locations. Useful data included the median household income expressed as dollars per year per household and housing density measured in dwelling units per unit square kilometer (DU/km^2).

To express housing density (dwelling units per area), the simple computation of dividing the number of dwelling units per census group block by the area of the census group block was done. Housing density is used to measure urban development encroachment into the wildland areas. As one moves from an urban center, the number of dwelling units per acre decreases and one expects that in ideal wildland areas no dwellings would be present. For this project a conservative figure of 1 to 20 dwelling units per square kilometer was initially used to identify the urban-wildland interface zone. This range is appropriate and reflects the low population of the county.

Median household income was used to measure the economic activity of landowners. It has been hypothesized that with higher income, one's interest in the environment becomes more varied. In certain cases this can be focused on the value of the land as a means of making a livelihood, while in others it may be focused on the concerns for the environment (Smith 1994).

PC ARC/INFO, a popular GIS development package, was used to overlay the data layers and create the database using polygon and line topology. PC ARC/INFO stores its data files in dBase format; this is useful for complete integration of data from other sources such as the TIGER/Line files. Additionally, this package allows for easy updating of both spatial and attribute information.

RESULTS

LeFlore County

The data coverages were imported into ArcView, a powerful GIS end-user package. This software provided the means to visualize, explore, and analyze the database spatially. ArcView also allowed the building of very sophisticated queries to identify specific data combinations. Boolean operators such as "and," "or," "less than," "greater than," and "equal to" were used in the design of queries.

The query tool in ArcView allows an analyst to select features and records in a table that relates to the attributes values. Using this tool, the following query was built. An area is considered to be an urban-wildland interface if the following set of criteria is met: areas are outside town boundary limits; land cover is "rangeland" or "pasture" or "pine" or "hardwood"; housing density is greater than or equal to 1 but less than or equal to 15 DU/km^2; median household income is greater than or equal to $6,000 but less than or equal to $12,000 per household per annum. This is Criteria #1 and can be expressed by the following:

((([Leftowns] = 16) or ([Leftowns] = 0) and
(([class] = "rangeland") or ([class] = "pasture") or
([class] = "pine") or ([class] = "hardwood")) and
(([Housing density] >= 1) and ([Housing density] <=
15) and
([Median household income] >= $6,000) and ([Median
household income] <= $12,000))).

Different sets of attributes or numerical values that lie within the range of the values found in the database were used in the construction of other queries. This feature of ArcView made it useful in exploring the outcome of other predictions by altering the values. It is one of a large number of possible combinations resulting from changing the values of the attributes. For this study, six sets of criteria or scenarios were chosen (table 1).

Criteria #1, previously outlined, results in a potential urban-wildland interface area totaling 38,498 ha (95,129 acres). Criteria #2 modifies the first criteria to show a range of the housing density of 1-20 DU/km^2 and a median household income of $10,000-$20,000. The resulting interface has an area of 35,327 ha (87,291 acres).

The predicted interface zones can be illustrated with graphic output. The interface zone predicted by Criteria #1 is concentrated on the western border of the county (fig. 1). Criteria #2 is similar to the first criteria except that additional interface zones now extend from the concentration on the western border in a northeasterly direction, following a major highway (fig. 2). Graphic output was generated for each of the other four criteria. This allowed comparisons of predicted interface locations.

Criteria #3 explores the effect of median household income in the high range values (for LeFlore County) of $20,000 to $32,000 along with a low housing density range of 1-15 DU/km^2. The predicted interface is found to be concentrated around the edges of the major towns in the northern section of the county. The area of the interface defined by this prediction is 63,813 ha (157,681 acres). Mechanized agriculture is the dominant activity in this region, and this is reflected in the high median household income values. Potential conflicts are likely to occur when such activities are present. Wildland encroachment for farm expansion and effects of farming activities (poultry and hog production) can have undesirable impacts on water quality in the surrounding areas.

In an attempt to evaluate the prediction capability of the housing density, the median household income variable was left out of the query used in the construction of Criteria #4. The result shows a large predicted interface with an area of 89,443 ha (221,011 acres), concentrated in the northern and western sections of the county. Not surprisingly, the areas follow major roads and occur adjacent to towns in areas of high agricultural activities. The predicted area is similar to that predicted by Criteria #3. This is expected as the numerical values of the variables in Criteria #4 are captured in Criteria #3.

Table 1.—*Summary of six different combinations of attribute values used to define potential urban-wildland interface zones*

Criteria number	Outside of town limits	Land cover class	Housing density	Median household income
			#/km^2	
1	yes	pine, hardwood, pasture, rangeland	1 - 15	$6000 - $12,000
2	yes	pine, hardwood, pasture, rangeland	1 - 20	$10,000 - $20,000
3	yes	pine, hardwood, pasture, rangeland	1 - 15	$20,000 - $32,000
4	yes	pine, hardwood, pasture, rangeland	1 - 10	not used
5	yes	pine, hardwood, pasture, rangeland	not used	$6000 - $18,000
6	yes	pine, hardwood, pasture, rangeland	1 - 10	$6000 - $18,000

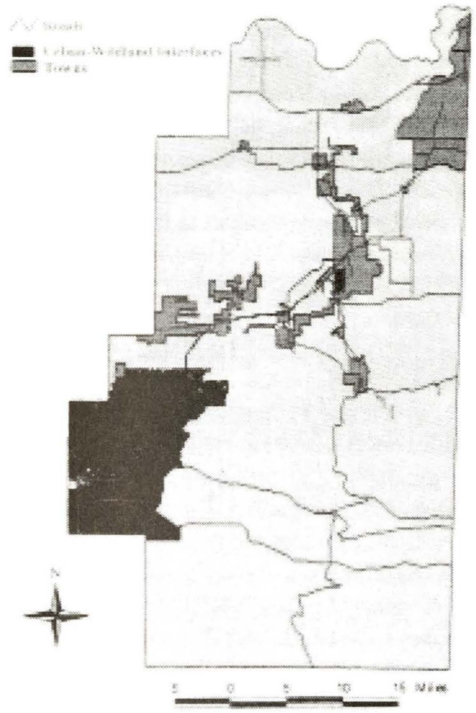


Figure 1.—*Map of LeFlore County, Oklahoma, showing the urban-wildland interface locations, as predicted by Criteria #1, overlaid with thematic map of town boundaries.*

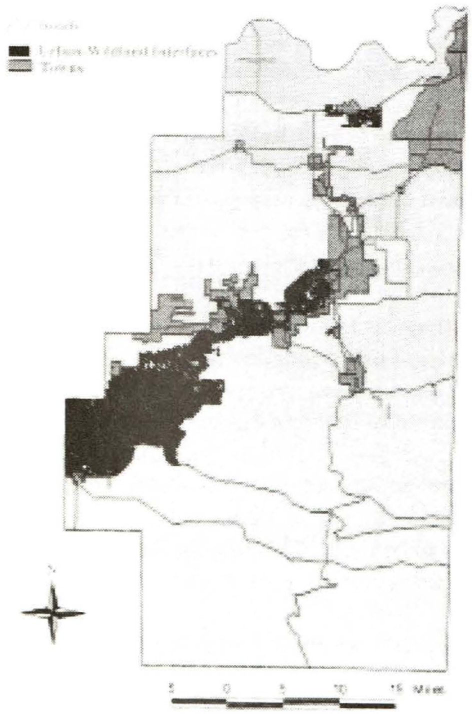


Figure 2.—*Map of LeFlore County, Oklahoma, showing the urban-wildland interface locations, as predicted by Criteria #2, overlaid with thematic map of town boundaries.*

A similar query (Criteria #5) was built for the median household income, leaving out the housing density variable. The result shows the predicted interface to be concentrated in the middle part of the county. The area predicted by Criteria #5 is 91,495 ha (226,083 acres).

Finally, Criteria #6 was built to include lower range values for both the housing density and the median household income; the values are 1-10 DU/km^2 and \$6,000 to \$18,000, respectively. The predicted interface has a total area of 37,595 ha (92,896 acres), closely matching that predicted by Criteria #1 and #2. However, the area defined by Criteria #6 is much more highly fragmented.

For all six criteria used, the southern portion of the county showed no area as potential urban-wildland interface. This region has a very low human population and very low economic activity, and a large percentage of the area is part of the Ouachita National Forest. The consistency of five of the six criteria in predicting the area in the vicinity of the town of Talihina was also noteworthy. Perhaps, there are merits in looking more closely at this location in a future study.

Procedure for Defining the Urban-Wildland Interface

The purpose of this study was to develop a model for defining the urban-wildland interface. The model resulted in a step-by-step procedure that is simple, concise, and iterative. This procedure includes steps involving data acquisition, preparation, analysis, and output:

Data Acquisition

1. Remotely sensed digital data are important sources of land-use/land-cover information. These data are available in several formats such as LandSat MSS, LandSat TM, and SPOT. Data from this source must be registered to a predetermined coordinate system such as the Universal Transverse Mercator (UTM). Registration allows for spatial analysis of real world geography. Extraction of useful information is done by analysis of the properties of the raster or vector values using computer algorithms available in GIS software packages.

2. The Housing and Population files found in the US Census Bureau's TIGER/Line files can provide data for the median household income and the housing density. These files also contain digital data depicting town boundaries and roads.

Data Preparation

1. Remotely sensed data can be classified into land-cover types using supervised and unsupervised

techniques. Results should be ground truthed to ensure classification accuracy is acceptable.

2. The data in the TIGER/Line files are stored in digital format and, using Arc and Arc Plot software, can be transformed into lines and polygons. Using Arc/Info, topology can be created from the lines and polygons, simultaneously building Arc Attribute Table and Polygon Attribute Tables. These tables can then be later joined with the polygons for the land cover-types within Arc/Info. This results in the required database.

Data Analyses

1. The database can then be imported into ArcView, where data manipulation, construction of queries, and visual display of the result of the queries may be performed. Query construction is facilitated using several query building tools available in ArcView. Building queries is constrained only by the numerical values of the fields within the database and the number of records contained in it. For example, the following query can be constructed:

(((([Leftowns] = 16) or ([Leftowns] = 0) and
((([class] = "rangeland") or ([class] = "pasture") or
([class] = "pine") or ([class] = "hardwood")) and
((([Housing density] >= 1) and ([Housing density] <= 15) and
([Median household income] >= $6,000) and ([Median household income] <= $12,000))).

2. The versatility of ArcView enables an analyst to alter the numerical values within the range provided for selected variables or to eliminate certain variables when building the queries. The example below illustrates several altered values (shown in bold):

(((([Leftowns] = 16) or ([Leftowns] = 0) and
((([class] = "rangeland") or ([class] = "pasture") or
([class] = "pine") or ([class] = "hardwood")) and
((([Housing density] >= 1) and ([Housing density] <= **20**) and
([Median household income] >= **$12,000**) and ([Median household income] <= **$24,000**))).

Data Output

1. The visual display on the computer monitor can be used to make high quality maps by using the Layout feature of ArcView. Layout allows one to control the appearance of the finished product. Hard copies in the form of transparencies and maps can be obtained by using a color printer such as Hewlett Packard XL300 PaintJet printer.

2. Results pertaining to the areas of the urban-wildland interface can also be presented in tabular format and statistical parameters such as means, standard deviations, summations, and ranges are easily obtained using the Statistical function in ArcView. The selected records for each query determine the predicted area, which can be converted to a shape file and added as a separate theme in another View or exported as a theme to another vector-based GIS package.

CONCLUSIONS

The model developed in this study has the potential to provide valuable information to forest managers, county officials responsible for land-use policies, and city planners in LeFlore County. Relevant data were acquired and created from existing sources, sorted and evaluated, and entered as coverages (layers of information) into a computer format. The database was designed using a popular and easily accessible GIS package: PC ARC/INFO. This package allows the input, manipulation, and easy display of data. Using ArcView, an end-user GIS display software that is compatible with PC ARC/INFO, queries were built and likely interface zones visually displayed. A number of queries relating to these coverages were designed which would identify an area as being an urban-wildland interface. This proved the versatility and usefulness of the model.

One of the objectives of this study was to evaluate the variables that can be used in developing the set of procedures. This resulted in using four layers: housing density, median household income, town boundary limits, and land-cover types. Areas are considered as potential interface zones if they occur outside of town boundaries and satisfy required values for land cover, household income, and housing density.

Another objective was to evaluate the potential application of the model to other counties or regions in the southeastern United States. For areas near LeFlore County, application of this process would seem to be feasible and permissible. For other regions, however, physical land-cover differences and different patterns of socioeconomic activities may dictate that a different set of variables needs to be used. This may be a different number of variables or different types of variables.

Problems associated with the urban-wildland interface zones are major issues in natural resources management. The interfaces are zones where social, economic, and political factors interact in complex ways. Problems are often social and institutional rather than technical. The need for better tools to handle ever more critical natural resource problems is obvious, and the rapidly developing field of information technology provides the necessary machinery. GIS is a very powerful tool for analyzing vast amounts of spatial data that can aid in developing an understanding of the importance of the variables that define the interface zone. However, the limitations of GIS must be carefully considered when using the results produced from this approach for decisionmaking. More elaboration and analysis of the social aspects as related to the inhabitants of these zones needs to carried out. As they begin to understand the values, preferences, and attitudes of new residents, resource managers will be better able to demonstrate their role and responsibilities in issues relating to the interface zones.

ACKNOWLEDGMENTS

The following people reviewed this manuscript: Roger Williams, Assistant Professor of Forestry, The Ohio State University; Columbus, OH, USA, and Tom Hennessey, Professor of Forestry, Oklahoma State University, Stillwater, OK, USA.

LITERATURE CITED

Alig, R.J.; Healy, R.G. 1987. Urban and built-up land area changes in the United States: an empirical investigation of determinants. Land Economics. 63(3): 215-226.

Chun, A.V. 1996. Development of a model for defining and predicting the urban-wildland interface for LeFlore County, Oklahoma. Stillwater, OK: Oklahoma State University. 93 p. M.S. thesis.

Lee, R. 1984. Implication of contemporary community organization and social values for forest management on the residential/wildland interface. In: Bradley, ed. Landuse and forest resources in a changing environment: the urban/forest interface. Seattle, WA: University of Washington Press. 222 p.

Oklahoma Department of Commerce. 1993. Statistical abstracts of Oklahoma. Oklahoma City, OK. 278 p.

Smith, Z.A. 1994. The environmental policy paradox. Englewood Cliffs, NJ: Prentice Hall. 255 p.

Using Sampling Theory as the Basis for a Conceptual Data Model

Fred C. Martin, Tonya Baggett, Tom Wolfe, and Roy Mita

Abstract.—Greater demands on forest resources require that larger amounts of information be readily available to decisionmakers. To provide more information faster, databases must be developed that are more comprehensive and easier to use. Data modeling is a process for building more complete and flexible databases by emphasizing fundamental relationships over existing or traditional business operations. Data modeling uses a hierarchical series of models beginning with a conceptual model of the activity of interest. From the conceptual model, a logical model is derived that captures more detail, but in an implementation-independent way. Finally, the logical model is transformed into a physical data model by means of application software. We show how sampling theory was used in a conceptual model to provide an integrating framework for identifying fundamental relationships. By using sampling theory, the final data structure organizes forest vegetation data gathering as a scientific process, rather than as specific business functions.

A data model is "a picture or description which depicts how data is to be arranged to serve a specific purpose" (Modell 1992). Without such a model, developers are prone to build data systems that incorporate existing relationships instead of more fundamental data relationships. The rapidity with which forest values are evolving and the complexity of forest resource data attest to the need for comprehensive data systems. The high cost of such systems motivates the use of modeling procedures and design concepts that promise longevity, flexibility, and stability. Although only one of several data management issues, the storage and availability of forest inventory and other vegetation measurements are crucial to the credibility of any management information system.

Social forces altering forest management activities are creating demand for resource information previously considered of little value. Small wood marketing requires information on ever smaller logs, while the resulting thinned stands prompt re-inventory of conditions largely ignored in the past. Forest practice laws requiring retention of residual live and dead trees create a need to "track" relicts and to develop inventories on dead woody materials. In addition, research continues to highlight dimensions of the forest not traditionally examined; recent examples include managing woody debris in forests (Graham *et al.* 1994), the need for risk assessment of refugia-like forests (Camp *et al.* 1997), and recognition of highly diverse forest structures important for endangered species (Everett *et al.* 1997). These events have led to expanded inventories that include new elements and characteristics such as snags, dead woody material, stumps, platforms and cavities, understory plants, canopy structure, and successional status.

Because of the extensiveness of forest vegetation data and the need for user support, larger integrated data structures are being promoted. Multiple small databases are simpler, but each system is supported by fewer people, while larger data systems allow redundancy in support personnel. A tradeoff is made for larger support capability at the expense of greater complexity. The difficulty of keeping separate systems functioning with changing events and technology is also seen as a benefit of a larger integrated system, e.g., year 2K transition, distributed processing, etc.

The purpose of this paper is to show how sampling theory was used to guide the development of a forest vegetation database. Sampling theory aided in the integration of disparate business operations into a single structure and provided principles for evaluating data model logic. We believe that sampling theory provides the foundation for more stable and longer lived data structures.

STEPS IN DATA MODELING

A basic issue in database development is how to deal with the sheer volume and complexity of data generated by our activities. This is not a trivial issue; how one chooses to organize data for storage has a profound bearing on the

---

Forest Biometrician, Washington Department of Natural Resources, Olympia, WA, USA; Computer Programmer, USDA Forest Service Forest Management Service Center, Ft. Collins, CO, USA; Systems Analyst, Washington Department of Natural Resources, Olympia, WA, USA; Operations Research Analyst, USDA Forest Service Forest Management Service Center, Ft. Collins, CO, USA.

subsequent ability to retrieve and use it. History, even recent history, is filled with examples of data structures that could not pass the test of daily use. How does one organize data so that they can be readily stored, retrieved, and, most important, used? How can different organization units share the same data? How can redundancy and its consequent implications for rising maintenance costs and introducing errors be reduced? Lastly, how can all this be done and still maintain a level of flexibility, since processes and needs change over time?

One approach is data modeling. In an earlier age, data models were simple and largely intuitive. However, as data and the demands of end users have increased, both the building process and the model itself have become increasingly complex. The payoff to thorough data modeling is a system that is comprehensive, flexible, and reliable.

A precursor to data modeling is business function modeling, which begins by reviewing business practices and products to determine business requirements for a data structure (Barker and Longman 1992, Baskerville and Moore 1988). This process progresses through a series of steps to identify the hierarchy of functions executed by an enterprise. High-level forestry business practices include inventory, timber cruising, land appraisal and exchange, experimentation, monitoring, regeneration certification, and timber sale compliance surveys. The process of examining different functional levels ultimately leads to identifying elementary business functions. Examples of elementary business functions (tasks that once started must be completed entirely to be useful) are inventory projections, measurement of vegetation data (sampling events), calculation of population parameters, and outputting of tree lists for further modeling. An important result of business function modeling is identification of function commonality. Commonality occurs when data can be shared between more than one business function, e.g., collected tree data are used to estimate parameters needed for timber sale, land exchange, habitat assessment, etc. Identifying relationships and dependencies between different functions is the basis for model building and is crucial to eliminating data redundancies. Examination of the relationships between elementary, common, and dependent business functions revealed sampling to be an integral part of all elementary functions and that all high-level functions relied on population parameter estimates.

The process of data modeling follows business function modeling. Data modeling designs a database using a series of related hierarchical models (Weldon 1997). The first modeling level is a conceptual model of the primary business activity to be supported; the business activity considered here is sampling. Based on the conceptual model, a logical model is developed that captures specific data items and relationships in a logical but application-independent way. Lastly, a physical model is constructed that implements the data and relationships of the logical model using a specific database management system (DBMS), such as Oracle. Limitations on the physical implementation may arise because the DBMS is unable to achieve all of the relationships identified in the logical model, or they may arise from basic business constraints such as limited computer capabilities or staff expertise.

Recognition that sampling data were being stored and manipulated confounded traditional database expectations—a paradigm shift was required. In a conventional database system, each "record" (observation, instance) is important in its own right, i.e., assumed a true population parameter known without error. A business payroll database lists every individual, their position and salary; no variance or sample error is considered or allowed. Each record represents only itself and every record is critical. But, when dealing with sample data, the interest is in parameters of sampling distributions that are related to a fundamental probability set (or population) and to sample size (O'Regan and Palley 1965). The identity of an individual element is less important than its contribution to a parameter estimate. For example, line-intersect sampling of a piece of woody material estimates volume per unit area, not volume of the observed piece; a regeneration survey returns a stocking sufficiency value and the identity of any particular seedling is insignificant; and the presence of a tree on a variable-radius plot estimates basal area per unit area and individual tree dimensions are less important. The expected value of a *population* is the information of primary interest, not the value of a single object. The population estimate is more important than the sampled element.

In a "sample" data system, information does not equal data. Data are facts used to *infer* information; information is knowledge about a population of interest. Sample data are the measurements about a population used to *derive* information. Rarely are sampled data the principal objects of concern; rather, they are a means to an end. This paradigm shift required that sampling and data modeling requirements be integrated. Important requirements in sampling consist of defining objectives, identifying populations, selecting a sample, making measurements, and estimating parameters. Important data modeling requirements are capturing fundamental versus existing relationships, eliminating redundancy and enhancing data integrity. Examples of fundamental relationships in forest measurements are recognizing that dbh is both a diameter *and* a height measurement, that crown ratio is just a ratio of height measurements, and that Girard form class is an arbitrary stem form measurement. Eliminating redundancy improves the quality of both data and processes, reducing problems with updates, and seeking a single "best" data storage location. Good modeling designs integrity into the data model rather than imposing integrity through external processes. Relationships between basic entities can enforce integrity, eliminating multiple code checks and redundant attributes. For example, by including event entities in the model, knowledge and counts of occurrences (such as plot "taking") are explicit without the need for additional attribute counters.

CONCEPTUAL DATA MODEL DESCRIPTION

Cochran (1977) listed 11 principal steps in a sample survey. Steps relevant to data model design are the objectives of the survey, population to be sampled, data to be collected, degree of precision desired, methods of measurement, the frame, selection of the sample, and summary and analysis of the data. These steps were redefined into eight conceptual data model entities (fig. 1).

1. Sample design
2. Population rule
3. Element selection rule
4. Characteristic measurement rule
5. Conceptual population
6. Sample event
7. Sample element
8. Measured characteristic

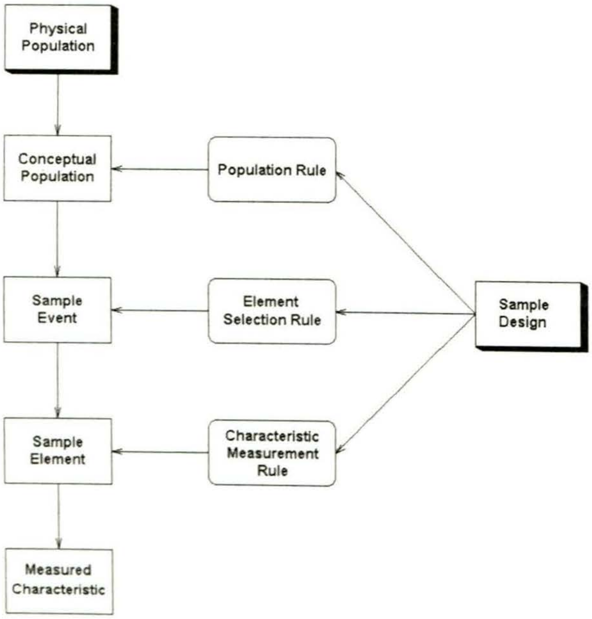


Figure 1.—*Conceptual model entities and relationships for a sampling survey database.*

Building the conceptual model involved defining the entities, recognizing their relationships, and identifying instances of each entity type. Entity definitions were influenced by previous work of Palley and O'Regan (1961), O'Regan and Palley (1965), and Byrne and Stage (1988).

The sample design, population rule, element selection rule, and characteristic measurement rule entities (fig. 1) together form the protocol (metadata) for describing instances of sample events, sample elements, and measured characteristics. A sample design entity specifies the purpose and type of survey, the parameters to be estimated, and the number of conceptual population levels prescribed for the survey. Different types of surveys lead to different conceptual population hierarchies, e.g., a simple stand inventory has fewer population levels than a stratified multistage design. Conceptual populations originate from physical populations by application of population and element selection rules creating "sampled" populations for a specific design. Physical populations are the set of physical objects about which we desire information; it is the "target" population, such as all the trees in a stand or in a forest. Sometimes the target and sampled populations are the same, but often there are "gaps" between them. A physical population can be sampled with many different designs, each design creating a distinct set of conceptual populations. For example, a watershed may be intensively sampled using a "wall-to-wall" stand-level inventory design, or it may be sampled as part of a stratified extensive sample. Each design defines a different set of conceptual populations from the same physical population. A sample design protocol is static over time; changes to any of the protocol entities create a new design. Relationships between the design protocol entities and the instances of sample events, elements, and characteristics ensure integrity between the "why, where, and how" of a survey and the "what and when" of data collection.

Population rules establish the hierarchy of nonoverlapping conceptual population levels for a design (fig. 2). The rule describes the type and form of conceptual populations at each hierarchical level. For example, in stratified sampling, the population as a whole is the top-level population, strata compose the second level, and sample point locations form the lowest level. The top-level physical population might be a forested region, while the top-level conceptual population consists of all lands within mapped strata, where each stratum consisted of units greater than some minimum mapping-unit size. Likewise, an experiment might be composed of blocks, containing replicates of treatment plots. An experiment top-level conceptual population could comprise the totality of elements that might be treated in some fashion, as in a random effects model. The blocks may occupy physical areas, such as harvest units, while conceptually

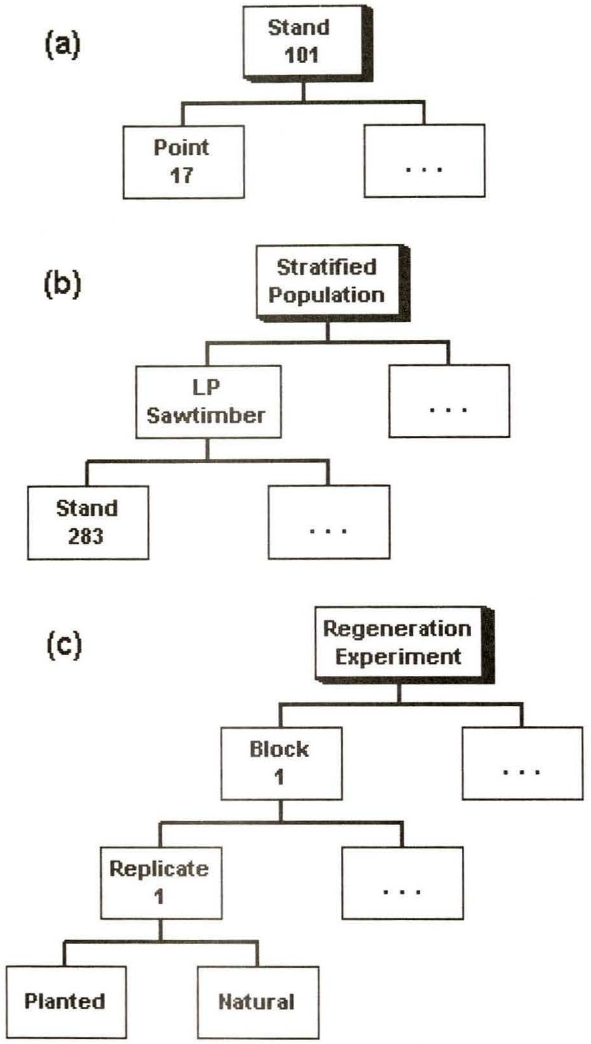


Figure 2.—*Schematic examples of conceptual population hierarchies for: (a) a single stand inventory, (b) a stratified stand inventory, and (c) a randomized complete block experiment.*

they represent a random sample of a harvest method. Similarly, a timber sale might be described by two population levels, a single harvest unit and a set of sample points; or it may require three levels—a top-level population for the entire sale, multiple second-level timber-harvest units, and sets of third-level sample point populations within each harvest unit. Besides defining the sampling frame, population rules also specify methods for determining probabilities (weights) at each hierarchical level. Conceptual populations may be spatial objects comparable to physical populations (polygons, lines, or points), they may encompass multiple physical locations, or they may represent theoretical populations. Further, for multiple resource inventories, a conceptual population may include several different types of elements; in essence, the population becomes a superset of different types of elements, each of which may be separately sampled from the population using different element selection rules.

Element selection rules define for each population level the types of elements to be sampled, the methods by which elements are selected for sampling, and criteria for creating subpopulations of elements. A population level may be sampled with many different selection rules, but a selection rule is unique for each population level; the same rule cannot be applied to the same set of elements at different population levels. This ensures that double counting does not occur. Further, within a sample design, element selection rules must be mutually exclusive so that the same individual element cannot be sampled with more than one rule. However, the same element may occur in two populations at the same hierarchical level, e.g., clustered variable-radius plots in which the same tree is observed at two or more points. The element selection rule also specifies the method for identifying which instance of an element is selected for sampling (e.g., fixed-area plots, horizontal point sampling, line intercept, 3P, census, etc.). Finally, the selection rule establishes criteria for creating subpopulations of elements (e.g., large trees versus small trees), each subpopulation of elements associated with a different sample selection rule. Examples of element selection rules are illustrated for a hypothetical "new forestry" timber sale cruise. Three conceptual population levels are defined: the harvest unit, several strips, and a systematic grid of points. For the top-level harvest unit population, select all large (>32-inch dbh), live cedar trees using 3P (rule 1) and select all large snags (>20-inch dbh) (rule 2). Within each strip (population level two), select all sawtimber-size live trees, except large cedars (rule 3). At each systematic point, select pieces of dead down wood with a 50-foot line intercept transect (rule 4), select understory vegetation groups (forbs, grasses, and shrubs) using a 1-m square grid (rule 5), and select all small snags (> 10 feet tall and < 20-inch dbh) using a variable-radius plot (rule 6). Over time the method appropriate for a specific element may change as the element moves from one subpopulation of elements to another. This causes no problem because sample event integrity is maintained (see below). The element selection rule is similar in concept to that described by Byrne and Stage (1988), but unlike Byrne and Stage, an element cannot be sampled with more than one selection rule in a given sample design. A change in the element selection rule results in a change in sample design and creation of different conceptual populations. However, this does not preclude evaluating sample results from multiple conceptual populations created from the same physical population. Such evaluations are effected by the relationship between conceptual and physical populations rather than through "linking variables" applied to individual measurements, as in the Byrne and Stage design.

A characteristic measurement rule controls which characteristics of elements are measured and the measurement protocols. Measurement controls include the order that characteristics are measured, criteria for deciding if a characteristic is to be measured, and the probability and minimum frequency of measurement. The order that characteristics are measured, along with measurement criteria, can be used to control which characteristics of an element are to be measured. For example, tree age might be observed if measurements of species, tree size, and damage were all within specified bounds, i.e., a site tree. Subsampling of characteristics is provided by specifying both a probability and a minimum frequency of measurement; e.g., subsampling of tree heights might specify measuring 25 percent of heights with a minimum of four heights per species. Measurement protocols include units of measure, acceptable measurement procedures and devices, measurement resolution, and legitimate values. Including units of measure within rules, rather than as attributes of actual measurements, reduces redundancy and enhances data integrity. Specification of procedure, device, and resolution attributes help document data quality. Legitimate value attributes provide filters to omit recording of extreme characteristic values, e.g., excessive ages or minor damages. Storing legitimate values (particularly for categorical or class values) in the design protocol allows new designs to evolve while protecting data integrity. For example, if class values change over time (e.g., tree damage codes or structural stage classes), originally recorded values are retained but made equivalent to current values through translation tables, a process known as image journaling.

Application of the population rules to physical populations creates specific instances of conceptual populations. These instances are recursive within the defined population hierarchy, forming a parent-child relationship. Information for higher level populations can be inferred from information at lower levels, while lower levels "inherit" characteristics from higher levels. Usually an instance of a conceptual population is defined on a physical population identifiable by a closed polygon, line, or point. However, as previously mentioned, some populations may not be directly related to physically identifiable populations, such as in an experiment. Two important population attributes are the area (when it exists) and the sampling weight. Sampling weight is especially important because different populations may be sampled with different probabilities, as in stratified random sampling. Keeping sampling weights with the population instance instead of with the population rule allows greater flexibility for applying the same design protocol to different physical populations. Assemblages of populations within levels and between levels with their appropriate weights permit estimating parameters for either *a priori* or *posteriori* populations.

A sample event entity is the application of an element selection rule to a conceptual population level at a specific time. The sample event is a pivotal entity for data modeling. It uniquely relates measurements of elements to a population for a point in time. The sample event "intersects" an element selection rule entity and a conceptual population entity bringing into being a cluster of elements (trees, dead wood, shrubs, etc.) with known probability of selection. A collection of sample events for a single type of element at a single point in time appears equivalent to the definition given to a "conceptual population" by Palley and O'Regan (1961) and O'Regan and Palley (1965). We use the term more broadly; a conceptual population can be a collection of sample events for a single element, or a collection of sample events for multiple element types, or even for a single sample event. The extent of elements encompassed by a conceptual population depends on the population level and the sample events associated with it. Different sampling events arise from application of different sampling rules to the same conceptual population, even when applied at the same time. However, sampling the same potential set of elements using a different element selection rule would constitute an entirely different sample design protocol, leading to a new set of conceptual populations and a new set of sample events. This condition, or constraint, maintains integrity between conceptual population weights and sample events within the same sample design protocol. For example, sampling trees in a stand using both variable-radius and fixed-radius element selection rules would require two separate design protocols resulting in two separate conceptual populations and two separate sample events, all for the same physical population. An important attribute of a sample event is the probability associated with the selected element(s). Although the element sample rule defines the basic sampling method, the precise probability of an element may not be known until or even after the time of element selection, e.g., 3P sampling and cluster sampling across type boundaries. The count of sample events from a single time for a given population level is equal to the sample size from that population; an additional sample size attribute is unnecessary. Assembling sample events for a given time is the first step in deriving parameter estimates for a population level.

Sample elements are the basic units of a population on which characteristic measurements are made. Element types defined to date are: (1) an individual tree; (2) a group of trees; (3) a piece of woody material; (4) an individual forb, fern, grass, or shrub; (5) a group of forbs, ferns, grasses, or shrubs; and (6) the surface of the land. Although elements may occasionally mimic sample units, such as in 3P sampling or single stage cluster sampling (Shiver and Borders 1996), they are always related to some population level through the sample event entity.

Instances of elements become part of a conceptual population sample by the application of an element selection rule. For example, a tree is included in a conceptual population if its distance from a point is within some proportion of its squared-diameter when applying a horizontal point selection rule; likewise, some of the land surface will be included in a conceptual population if it falls with the area of a fixed-radius plot. Each element is considered to have an area of influence; the conceptual population establishes a location from which an element's influence area is appraised using an element selection rule (Stage and Rennie 1994). An element can be selected using only one sample selection rule at a single time, but the same element can occur in several different conceptual populations, e.g., the same tree selected on two different variable-radius plots. Again, the marginal importance of a specific element is noted; the requisite information is provided by parameter estimates.

A characteristic is a quality or feature of an element that can be measured or assessed. Examples of quantitative characteristics include tree height, canopy cover of a group of trees, the aspect of the land surface, the cover of grasses, and the height of a shrub. Qualitative characteristics include tree crown class, tree group structural stage, decay class of a tree or piece of woody material, and land surface habitat type. Characteristics are the typical attributes found in forest databases, and their measured or assessed values are the data. Criteria for deciding which characteristics to measure and the probabilities and protocol for measurement are regulated by the measurement rule. A characteristic may be measured several times on the same element, e.g., multiple values of tree dbh using calipers or multiple damage agent classes for a group of trees. The number of times that characteristic values can be recorded for an element is determined by the final database structure.

INFORMATION GENERATION

Generating information is the *process* of assembling sample data and calculating population parameter estimates. Parameter calculation depends on the sample design including the probabilities associated with a measured element and its associated population level, as in stratified sampling. The process assembles element characteristic values from a set of sample events for a conceptual population and "expands" these values into a parameter estimate for the appropriate population. This assembly process may be iterative, estimating parameters at several levels of conceptual populations.

Parameter estimates need not be included in the database, but may be available on-demand as "views" or generated reports. Sometimes, parameter estimates will be generated and then used to "populate" attributes in related databases, such as a stocking table in a silvicultural database, a volume on a timber sale offering web page, or a listing of structural stages in a habitat monitoring system.

CONCEPTUAL MODEL APPLICATION

The concepts described have been used to build two different logical models (FSVEG of the USDA Forest Service and FRIS II of the Washington Department of Natural Resources) and one physical model (FSVEG). Although the two logical models differ in appearance, both implement a data-storage logic based on sampling fundamentals. However, neither model completely addresses all of the data management issues surrounding forest vegetation sampling due to the complexities of defining and translating sampling theory into physical entities and relationships. We continue to rely on separate supporting reports and maps to explain the full breadth of our sampling surveys.

ACKNOWLEDGMENT

Dr. James W. Flewelling, Biometrics Consultant, Kent, WA, USA, reviewed this manuscript.

LITERATURE CITED

Barker, R.; Longman, C. 1992. CASE*METHOD function and process modeling. New York: Addison-Wesley Publishing Co. 386 p.

Baskerville, G.; Moore, T. 1988. Forest information systems that really work. Forestry Chronicle. 64(4): 136-140.

Byrne, J.C.; Stage, A.R. 1988. A data structure for describing sampling designs to aid compilation of stand attributes. Gen. Tech. Rep. INT-247. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 20 p.

Camp, A.; Oliver, C.; Hessburg, P.; Everett, R. 1997. Predicting late-successional fire refugia pre-dating European settlement in the Wenatchee Mountains. Forest Ecology and Management. 94: 63-77.

Cochran, W.G. 1977. Sampling techniques, 3rd ed. New York: John Wiley & Sons. 428 p.

Everett, R.; Schellhass, D.; Spurbeck, D.; Ohlson, P.; Keenum, D.; Anderson, T. 1997. Structure of northern spotted owl nest stands and their historical conditions on the eastern slope of the Pacific Northwest Cascades, USDA. Forest Ecology and Management. 94: 1-14.

Graham, R.T.; Harvey, A.E.; Jurgensen, M.F.; Jain, T.B.; Tonn, J.R.; Page-Dumroese, D.S. 1994. Managing coarse woody debris in forests of the Rocky Mountains. Res. Pap. INT-RP-477. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 12 p.

Modell, M.E. 1992. Data analysis, data modeling, and classification. New York: McGraw-Hill, Inc.

O'Regan, W.G.; Palley, M.N. 1965. A computer technique for the study of forest sampling methods. Forest Science. 11(1): 99-114.

Palley, M.N; O'Regan, W.G. 1965. A computer technique for the study of forest sampling methods. I. Point sampling compared with line sampling. Forest Science. 7(3): 282-294.

Shiver, B.D.; Borders, B.E. 1996. Sampling techniques for forest resource inventory. New York: John Wiley & Sons, Inc. 356 p.

Stage, A.R.; Rennie, J.C. 1994. Fixed-radius plots or variable-radius plots? Designing effective inventory. Journal of Forestry. 92(12): 20-24.

Weldon, J.L. 1997. A career in data modeling. Byte 22(6): 103-106.

Interfacing Natural Resource Inventories With Forest Growth Models

Growth and Yield Model Application in Tropical Rain Forest Management

James Atta-Boateng and John W. Moser, Jr.

Abstract.—Analytical tools are needed to evaluate the impact of management policies on the sustainable use of rain forest. Optimal decisions concerning the level of management inputs require accurate predictions of output at all relevant input levels. Using growth data from 40 1-hectare permanent plots obtained from the semi-deciduous forest of Ghana, a system of 77 differential equations was developed to quantify the growth dynamics of the mixed-species rain forest. The models underlying the equations were developed for seven species groups, each with similar growth characteristics. This minimized the parameter estimation error. Simultaneous solution of the differential equations with initial stand conditions produced estimates of yield at some future time that was independent of stand age. The solution provides the means to project the status of the timber stand at any future time given well-specified initial stand conditions. The models are useful for inventory updating, allowable annual cut calculations, and management planning for natural or managed stands.

The absence of analytical skills and tools to determine optimal exploitation levels and evaluate the impact of alternative policies has hampered the sustainable use of the rain forest to provide the greatest benefit to all generations. Optimal decisions concerning the level of management inputs, felling cycles, cultural operations, and financial investments require accurate predictions of output from growth and yield models at all relevant input levels.

Therefore, the purpose of this study was to extend the existing analytical techniques to develop a planning tool that can help resource managers objectively evaluate the impact of management policies on the forest resource and implement procedures to maintain forest health. The accomplishment of this objective necessitated the development of a compatible *Growth and Yield Prediction System* that incorporated mechanisms for evaluating land-use policy scenarios based on cutting cycle, volume control, and economic harvests.

Using growth data from 40 1-ha permanent plots obtained from the semi-deciduous forest of Ghana, a system of 77 differential equations was developed to quantify the growth dynamics of the mixed species rain forest.

The models underlying the equations were developed for seven species groups, each with similar growth characteristics. This minimized the parameter estimation error (Atta-Boateng and Moser 1998). Simultaneous solution of the differential equations with initial stand conditions produced estimates of yield at some future time that was independent of stand age. In addition, stand structure data, expressed as stand and stock tables, were obtained from 110 1-ha temporal plots (Ghana Forestry Department 1989). These data were used to specify initial stand conditions.

METHODS

In modeling mixed-tropical rain-forest stand dynamics, this study identified individual components of growth, developed hypotheses concerning the mathematical functions describing the processes, and collectively expressed them as a system of equations capable of predicting the growth of the stand. This approach has been used in a number of studies (e.g., Moser and Hall 1969). The following notations are for per hectare stand variables by species class $k \in \{1,2,..,7\}$.

N_k^i, N_k^m, N_k^s : Sums of in-growth, mortality, and survivor trees

D_k^i, D_k^m, D_k^s : Sums of in-growth, mortality, and survivor tree diameters

B_k^i, B_k^m, B_k^s : Sums of in-growth, mortality, and survivor tree basal area

N_k, D_k, B_k : Sums of trees, diameters, and basal area (initial conditions)

$\delta N_k^i/\delta t, \delta N_k^m/\delta t, \delta N_k^s/\delta t$: Annual rates for in-growth, mortality, and survivor trees

$\delta D_k^i/\delta t, \delta D_k^m/\delta t, \delta D_k^s/\delta t$: Annual rates of change for sum of in-growth, mortality, and survivor tree diameters

---

Biometrician Research Forester, Mead Corporation, Rumford, ME, USA, and Professor of Forest Biometry, Department of Forestry and Natural Resources, Purdue University, West Lafayette, IN, USA, respectively.

$\delta B_k^i/\delta t, \delta B_k^m/\delta t, \delta B_k^s/\delta t$:	Annual rates of change for sum of in-growth, mortality, and survivor tree basal area
$\delta N_k/\delta t, \delta D_k/\delta t, \delta B_k/\delta t$:	Net change rate for sums of trees, diameters, and basal area
N^p, D^p, B^p :	Sums of trees, diameters, and basal areas (initial conditions)

Quantifying the Number of Mortality Trees and Stand Density Relationships

Mortality may differ in scale and intensity for various ecological reasons, and the underlying stochastic processes may not be comprehensible given the myriad of factors, including disease. This study predicted the number of mortality tree by the numerical integration of the density-related function:

$$\delta N_k^m/\delta t = a_{1,k} + a_{2,k} X_f(N_k) + a_{3,k} X_f(D_k, B_k) \qquad (1)$$

Where $a_{1,k}$ and $a_{2,k}$ are species class $k' \in \{1,2,\ldots,7\}$ parameters, and X_f is an expression involving the stand attribute satisfying the relationship. Equations (2) and (3) were used to force compatibility between predicted numbers, sum of diameters, and basal areas of mortality trees:

$$\delta D_k^m/\delta t = \alpha S_k / N_k \, \delta N_k^m/\delta t \qquad (2)$$

$$\delta B_k^m/\delta t = \beta \, B_k / N_k \, \delta N_k^m/\delta t \qquad (3)$$

Quantification of Size Distribution of Mortality Trees

To ensure a realistic number of mortality trees N_k^m, mortality rate equations were constrained by the limits specified by the probability distribution of mortality trees occurring within the period. Specifically,

$$f\ (x) = \frac{x^{\alpha_1 - 1}(1 - x)^{\alpha_2 - 1}}{\beta(\alpha_1, \alpha_2, x)} \qquad (4)$$

Where

$$\beta(\alpha_1, \alpha_2, x) = \int_0^1 t^{\alpha_1 - 1}(1-t)^{\alpha_2 - 1}\,\delta t \qquad (5)$$

Components of In-growth

In-growth refers to the process of trees reaching some specified lower size limit. This study predicted the number of in-growth trees by the solution of the following differential equation relating in-growth, number, and relative basal area of trees:

$$\delta N_k^i/\delta t = \alpha_{1,k} e^{\left(\alpha_{2,k} B_k / B^p + \alpha_{3,k} N_k\right)} \qquad (6)$$

Where $\alpha_{1,k}, \alpha_{2k}, \alpha_{3,k}$ are species class parameters. Basal area and sum of diameter growth rates of in-growth trees were constrained by tree in-growth rate using the equations:

$$\delta D_k^i/\delta t = \alpha_{1,k} + \alpha_{2,k}\,\delta N_k^i/\delta t \qquad (7)$$

$$\delta B_k^i/\delta t = \alpha_{1,k} + \alpha_{2,k}\,\delta N_k^i/\delta t \qquad (8)$$

Survivor Growth Functions

The choice of mathematical models to describe biological growth process has been the subject of many studies (Prodan 1953). This study fitted the derivative form of the Chapman-Richards function (Richards 1959, Chapman 1961) to model basal area and diameter growth of survivor trees.

$$\delta B_k^s/\delta t = \alpha_k \, B_k^{\beta_k} - \gamma_k \, B_k \qquad (9)$$

$$\delta D_K^s/\delta t = \alpha_K \, D_K^{\beta_K} - \gamma_K \, D_K \qquad (10)$$

Specification for Net Rates of Change

The following net growth in number of trees, sum of diameters, and basal area were used to predict future stand component values for trees of dbh ≥ 10 cm:

$$\delta N_k/\delta t = \delta N'_k/\delta t - \delta N_k^m/\delta t, \ \forall \ k \in \{1,2,\ldots,7\} \qquad (11)$$

$$\delta D_k/\delta t = \delta D'_k/\delta t - \delta D_k^m/\delta t + \delta D_k^s/\delta t, \quad \forall \ k \in \{1,2,\ldots,7\} \qquad (12)$$

$$\delta B_k/\delta t = \delta B'_k/\delta t - \delta B_k^m/\delta t + \delta B_k^s/\delta t, \quad \forall \ k \in \{1,2,\ldots,7\} \qquad (13)$$

Where $\delta N_k^i/\delta t$, $\delta N_k^m/\delta t$, $\delta D_k^i/\delta t$, $\delta D_k^m/\delta t$ t, $\delta B_k^i/\delta t$, $\delta B_k^m/\delta t$ and $\delta B_k^s/\delta t$ are as defined above.

Parameterization of Diameter Distribution Function

The system of equations provided the inputs for developing the following prediction equations for the parameters of the Beta:

$$\gamma_k = a_{11}\alpha_k + a_{12} \ln\left[(B_k/N_k)^{-1}\right] \qquad (14)$$

$$\alpha_k = a_{21}\gamma_k + a_{22} \ln\left[(B_k/N_k)^{-1}\right] \qquad (15)$$

The values for α_k and γ_k were obtained by simultaneous solution of equations in (14) to (15). The exponent K_k was obtained from the beta function:

$$\kappa_k = \frac{N_k}{\int_a^b (x - a)^{\alpha_k} (b - x)^{\gamma_k} \, dx} \qquad (16)$$

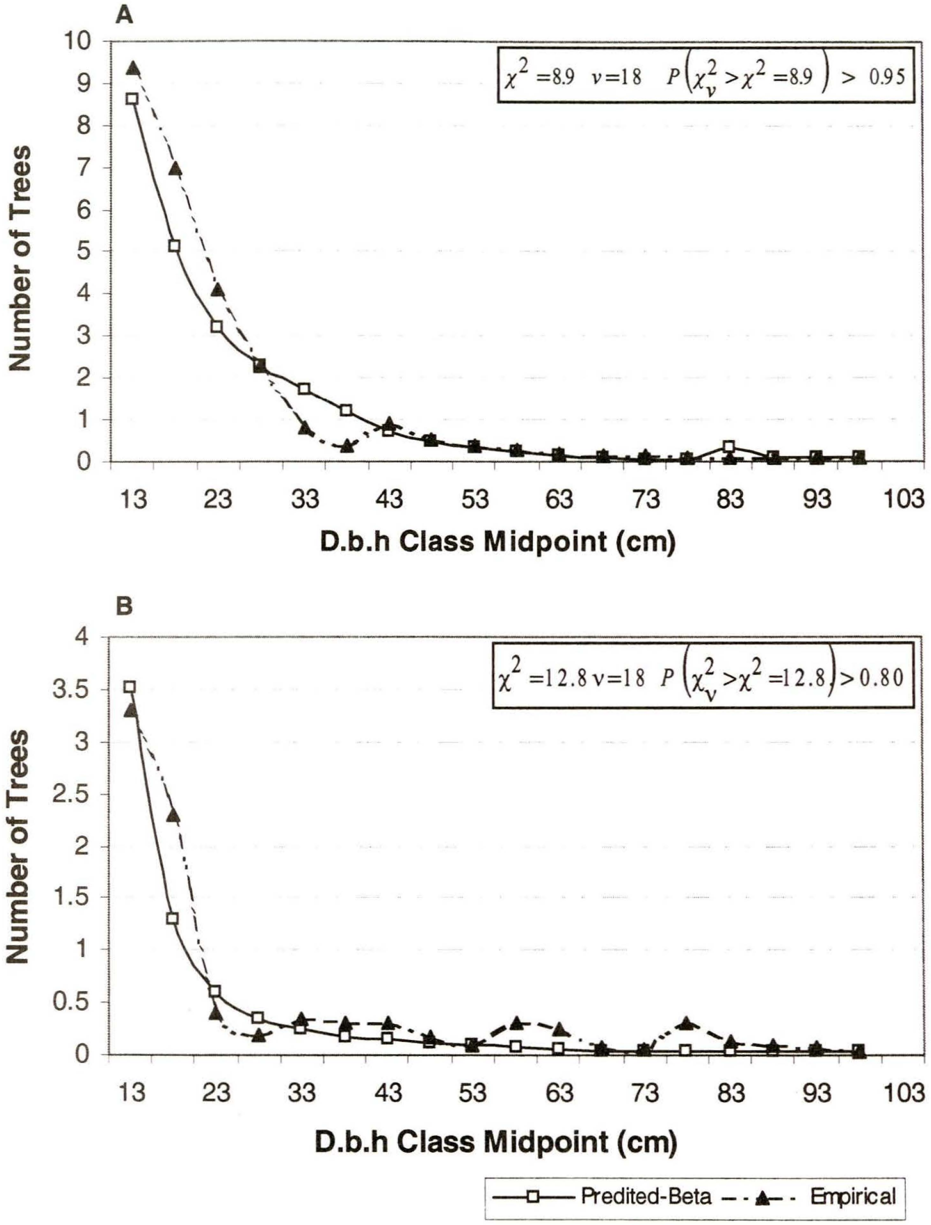


Figure 1.—*Comparison of empirical and predicted beta distributions for species classes within management unit 17. A. Class 1. B. Class 2.*

Figure 1 compares the empirical distribution, nonlinear optimized best-fit beta distribution, and the beta distribution obtained by equations (14) to (16).

The future predictions of stand components were used in models (14) to (15) to obtain estimates for the exponents of the beta distribution and subsequently generate the diameter distributions from which other forest management activities will be assessed.

RESULTS

Growth and Yield Consideration in Forest Management

Logging and timber stand improvement activities needed to maintain stand structures and regulate densities could be specified as harvesting rules. Rules may specify a percentage reduction in stocking in a size class. These considerations are implemented in the yield model to evaluate cutting limits, allowable cuts, and felling cycle lengths. Cubic volume cuttings that are sustainable under

Table 1.—*Stock table at year 5, 71-cm min. cut and 67 percent allowable cut regime*[1]

	Residual stand (km^2)			Harvest (km^2)		
Dbh (cm)	Trees	BA(m^2)	Volume(m^3)	Trees	BArea	Volume(m^3)
11-15	21,696	288.0	2,745.5	0	0.0	0.0
16-20	7,524	191.5	1,910.5	0	0.0	0.0
21-25	4,328	179.8	1,857.0	0	0.0	0.0
26-30	2,897	178.4	1,893.3	0	0.0	0.0
31-35	2,080	177.9	1,932.9	0	0.0	0.0
36-40	1,554	176.2	1,952.2	0	0.0	0.0
41-45	1,187	172.4	1,943.7	0	0.0	0.0
46-50	920	166.5	1,905.7	0	0.0	0.0
51-55	718	158.5	1,839.3	0	0.0	0.0
56-60	563	148.6	1,747.1	0	0.0	0.0
61-65	440	137.3	1,632.7	0	0.0	0.0
66-70	344	124.8	1,500.0	0	0.0	0.0
71-75	252	105.4	1,279.4	3	1.2	14.8
76-80	193	92.2	1,129.6	2	1.1	13.6
81-85	146	79.0	976.5	2	1.0	12.1
86-90	109	66.1	824.0	1	0.8	10.3
91-95	79	53.8	675.4	1	0.7	8.2
96-100	56	42.1	532.2	1	0.5	6.1
101-105	36	30.1	384.0	0	0.3	3.9
106 +	24	22.4	287.6	0	0.3	2.9
Total	45,146	2,591.0	28,948.7	11	5.8	72.0

[1] Stand defined by the Beta Distribution: $K_k = 0.0095$ for $\alpha_k = 0.9417$ and $\gamma_k = 2.3463$

Cumulative net basal area culminates at a simulation period of 60 years (fig. 4), with different final net basal areas. The magnitude of net basal area varies directly with minimum cut limit and inversely with allowable cut percent. Consequently, by combining minimum cut limit with an allowable cut percent a desired final net basal area can be obtained. Rate of accumulation of survivor basal area growth is lower than the other components of net growth. Most of the contribution to survivor growth comes from seedlings and poles and these have relatively smaller contributions of stand basal area.

Tables 2, 3, and 4 indicate that in-growth contributes significantly to the development of the stand. The rate of in-growth basal area accumulation contributes significantly to survivor basal area growth in subsequent periods of the simulation.

CONCLUSION

As the tropical timber industry enters the 21st century, it will search for competitive advantage in harvesting. Forest management will require intensive management and high yields. Forest managers will have to find ways to adhere to new environmental regulations and address the public's concerns about forest health. Better information and data analysis are the key to this new brand of intensive management.

This study is unique in the development of a window-based growth and yield system that incorporated a novel technique to pool sparsely distributed tropical forest tree species with similar growth increment characteristics into groups. The technique is a landmark in the construction of growth and yield models for mixed-species uneven-aged forest. It presents an objective approach to minimize the variations within each species group and hence the bias in the estimation of growth model parameters of the species groups.

The compatible growth and yield models developed were based on well-established premises.

ACKNOWLEDGMENTS

The permanent sample plot data were provided by the Forestry Department of the Ministry of Lands and Natural Resources of Ghana. The study was supported in part by

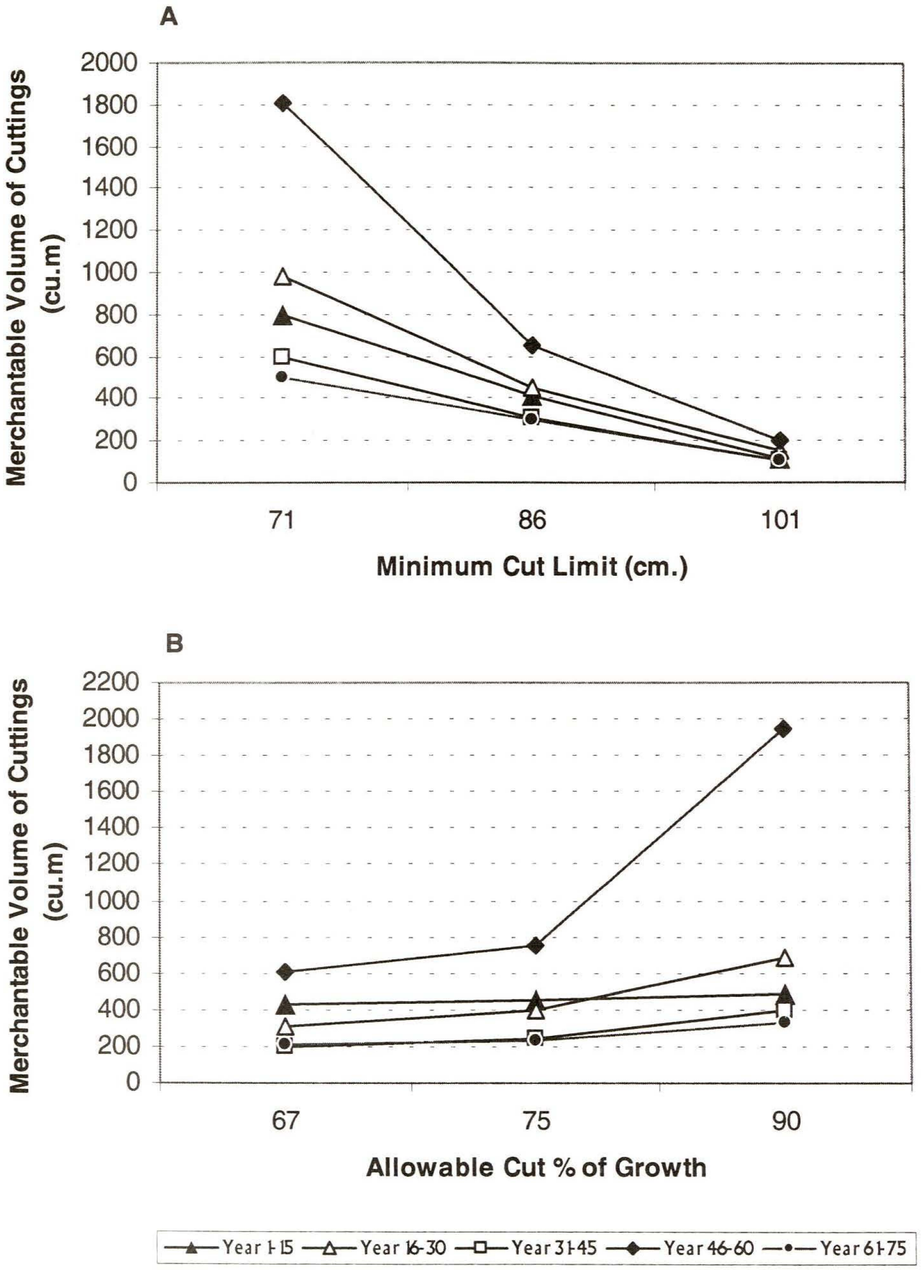


Figure 2.—*Merchantable volume of cuttings by allowable cut percent of growth, minimum cut limit, and planning period interactions for management unit 17.*

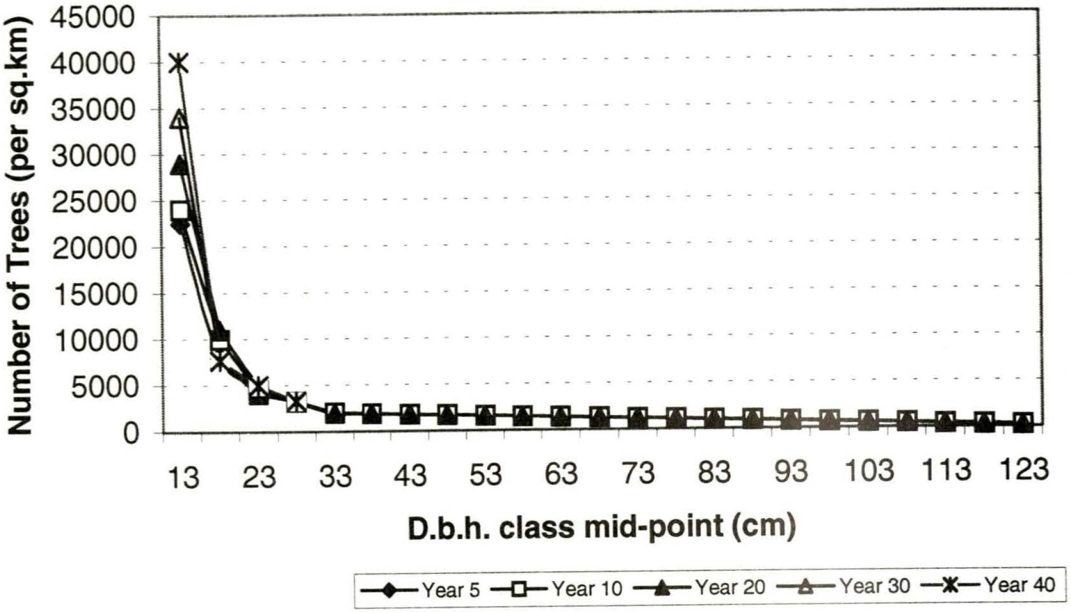


Figure 3.—*Projection of residual stand structures over a 40-year planning horizon.*

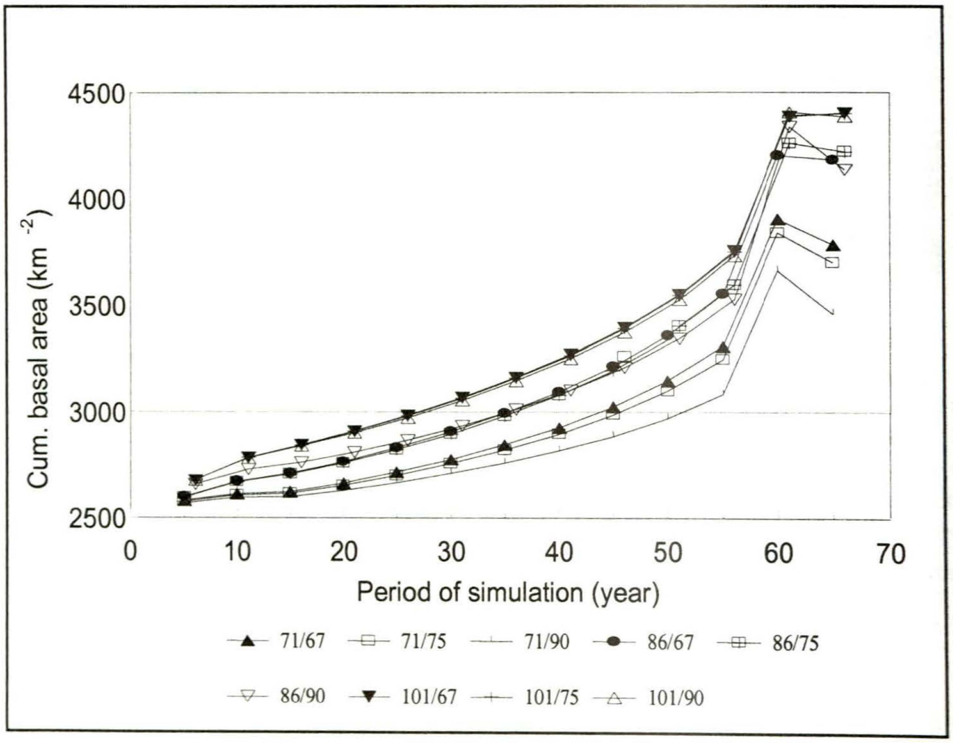


Figure 4.—*Cumulative residual basal area (km^2) by cut limit (first number) and allowable cut percent of increment (second number).*

Table 2.—*Cumulative in-growth basal area* (m^2 km^{-2}) *by minimum cut limit and allowable cut percentage*

Min. cut limit (cm)	Allow-able cut %	Simulation period (years)												
		5	10	15	20	25	30	35	40	45	50	55	60	65
71	67	83.5	165.2	250.0	340.0	435.8	538.5	650.2	773.3	912.7	1077.3	1287.3	1417.2	1790.4
71	75	83.5	165.2	250.2	340.2	436.2	538.8	651.0	774.5	914.5	1080.3	1292.3	1422.0	1797.0
71	90	83.5	165.2	250.2	340.7	436.7	540.2	652.7	777.2	918.7	1086.5	1302.8	1432.2	1811.0
86	67	83.5	165.3	250.0	339.7	435.2	537.5	648.7	771.7	910.5	1074.7	1285.0	1413.8	1864.0
86	75	83.5	165.3	250.0	339.7	435.3	538.0	649.3	772.7	912.3	1078.2	1290.8	1419.8	1874.4
86	90	83.5	165.3	250.0	340.0	435.7	538.8	651.3	775.7	917.3	1086.7	1307.0	1435.2	1905.2
101	67	83.5	165.2	249.7	339.0	434.0	536.0	646.3	767.7	905.0	1066.5	1271.2	1399.2	1840.2
101	75	83.5	165.2	249.7	339.0	434.2	536.0	646.5	768.5	905.8	1068.3	1274.5	1402.2	1846.6
101	90	83.5	165.2	249.7	339.0	434.5	536.7	647.5	770.2	908.7	1072.8	1283.5	1411.0	1865.2

Table 3.—*Cumulative survivor growth basal area* (m^2 km^{-2}) *by minimum cut limit and allowable cut percentage*

Min. cut limit (cm)	Allow-able cut %	Simulation period (years)												
		5	10	15	20	25	30	35	40	45	50	55	60	65
71	67	173.0	344.2	515.7	688.3	864.8	1045.8	1232.7	1426.8	1630.5	1846.0	2078.3	2557.0	3256.7
71	75	173.0	344.0	515.0	687.5	863.3	1043.8	1230.2	1423.8	1627.0	1842.0	2073.7	2551.5	3251.2
71	90	173.0	343.3	514.0	686.0	860.7	1040.0	1225.2	1417.2	1618.7	1832.0	2061.5	2536.2	3285.5
86	67	173.0	345.0	517.7	691.5	869.0	1051.3	1239.7	1435.5	1640.7	1858.3	2093.0	2579.3	3368.7
86	75	173.0	345.0	517.3	691.3	868.3	1050.5	1238.7	1434.2	1639.3	1857.2	2091.7	2580.5	3376.5
86	90	173.0	344.8	516.8	690.2	867.0	1048.7	1236.2	1431.3	1635.8	1853.3	2088.7	2647.3	3419.2
101	67	173.0	346.0	519.0	694.0	872.2	1055.2	1244.5	1440.8	1646.3	1864.2	2098.5	2581.8	3362.8
101	75	173.0	346.0	519.0	693.8	872.0	1054.8	1244.0	1440.3	1646.0	1863.8	2098.7	2583.5	3369.2
101	90	173.0	345.8	519.0	693.7	871.3	1054.5	1243.2	1439.5	1645.2	1863.0	2098.3	2588.2	3386.8

Table 4.—*Cumulative mortality basal area* (m^2 km^{-2}) *by minimum cut limit and allowable cut percentage*

Min. cut limit (cm)	Allow-able cut %	Simulation period (years)												
		5	10	15	20	25	30	35	40	45	50	55	60	65
71	67	85.2	217.8	403.0	591.3	780.8	973.7	1171.0	1373.8	1583.5	1800.7	2026.7	2271.2	2604.8
71	75	85.2	218.0	402.5	590.3	778.7	970.2	1166.2	1367.8	1575.3	1790.8	2015.0	2257.4	2588.2
71	90	85.2	218.0	401.8	587.5	774.0	962.2	1153.8	1350.7	1553.8	1764.2	1983.0	2220.0	2541.6
86	67	85.2	217.8	404.2	594.8	787.2	983.2	1183.3	1389.5	1602.8	1824.0	2054.8	2303.4	2726.8
86	75	85.2	217.5	404.0	594.0	785.8	980.8	1180.8	1386.3	1599.0	1819.5	2049.5	2297.2	2719.8
86	90	85.2	217.8	404.0	593.2	783.3	976.7	1174.5	1378.3	1589.0	1807.5	2035.5	2281.2	2701.2
101	67	85.2	217.7	405.0	597.3	791.7	989.5	1191.8	1399.7	1614.7	1837.7	2070.0	2320.2	2525.0
101	75	85.2	217.7	405.2	597.2	791.2	988.8	1191.0	1398.8	1613.7	1836.3	2068.8	2318.8	2745.2
101	90	85.2	217.7	405.2	596.8	790.5	987.2	1188.8	1396.2	1610.5	1832.7	2064.	2314.6	2741.4

grants from the Purdue University Graduate Program. Special thanks to Iris Boateng for typing and proofreading the manuscript.

LITERATURE CITED

Atta-Boateng, J.; Moser, J.W. 1998. A method for classifying commercial tree species of an uneven-aged mixed species tropical forest for growth and yield model construction. Forest Ecology and Management. 104: 89-99.

Chapman D.G. 1961. Statistical problems in dynamics of exploited fisheries populations. In: Proceedings, 4th Berkeley symposium of mathematical statistics and Problems. Berkeley, CA: University of California Press: 153-168.

Ghana Forestry Department. 1989. Ghana forest inventory project report. Departmental report. Accra, Ghana.

Moser, J.W.; Hall, O.F. 1969. Deriving growth and yield function for uneven-aged forest stands. Forest Science. 15: 183-188.

Moser, J.W., Jr. 1972. Dynamics of an uneven-aged forest stand. Forest Science. 18: 194-191.

Prodan, M. 1953. Verteilung des Vorrates gleichaltriger Hochwaldbestande auf Durchmesserstufen. Allg. Forst. U. Jagdztg. 129: 15-33.

Richards, F.J. 1959. A flexible growth function for empirical use. Journal of Experimental Botany. 10: 290-300.

Base-Age Invariance and Inventory Projections

C.J. Cieszewski, R.L. Bailey, B.E. Borders, G.H. Brister, and B.D. Shiver

Abstract.—One of the most important functions of forest inventory is to facilitate management decisions towards forest sustainability based on inventory projections into the future. Therefore, most forest inventories are used for predicting future states of the forests. In modern forestry the most common methods used in inventory projections are based on implicit functions describing time and site dependent relationships derived from panel data. The essence of the implicit functions used for inventory projections is that each function is defined by its own value at one point in time—usually at the inventory time—called the initial conditions or reference values. For this reason, these functions are also called self-referencing, and initial conditions are obtained from sampling, measurements, re-measurements, or other type of inventories. Classic examples of such functions, although not exclusive, are the site index models. They can have different algebraic forms using fixed or variable base ages and be base-age invariant or base-age variant. We explain the implications of different algebraic forms of the self-referencing models that can be used for inventory projections and discuss the forestry literature on base-age variant models under the base-age invariance agenda.

BACKGROUND

The models most frequently used in forestry to describe panel data, i.e., pooled cross-sectional and time-series or longitudinal or repeated measurements use self-referencing (Northway 1985) forms of site equations. In forestry almost all dynamic processes are necessarily dependent on the cross-sectional aspect of forest dynamics relating to different ecological productivity sites, hence: the site models. The site models are in principle the same as mixed-effects models (Lindstrom and Bates 1988, 1990), random-effects models for longitudinal data (Chi and Reinsel 1989, Laird and Ware 1982, Racine-Poon 1985, Stiratelli *et al.* 1984), and panel data models (Furnival *et al.* 1990). Yet, in forestry literature, they are most frequently referred to as site index models or site-dependent height over age models.

Different types of site models contribute immeasurably to efficient forest management by facilitating inventory updates and projections, growth and yield forecasting, and site productivity identification and stratification. These models are also the best illustrations of the evolution of site models in forestry and historical changes in site model forms and expectations.

The earliest efforts in height modeling concentrated on two-dimensional models (height over age). Both hand-drawn curves and the earliest equations that were capable of consistently generating more intricate shapes approximated two-dimensional relations. To enhance the applications of these two-dimensional relations, they could, at times, be developed separately for different sites or even individually for different stands. In a geometrical sense, the collections of curves developed separately for different sites or stands could be classified today as a discrete collection of two-dimensional polymorphic non-disjoint (Clutter *et al.* 1983) height curves.

Historically, such a collection was usually in the form of graphs or tables that were developed for a discrete collection of sites, or stands. They represented a four-dimensional height space in which the dimensions were: reference-height (discrete); age of reference-height (continuous); prediction age (continuous); and prediction height (continuous). The reference-height was reduced to discrete categories because only a discrete number of heights at any given age could be matched with existing curves.

For some applications, generic curves were anamorphically adjusted for individual stands by a simple means of manual multiplication of a guide curve using a ratio of observed to predicted height at an arbitrary age so that the newly generated curve would pass through a known height-age pair. Algebraically adjusting a single base model to specific situations or stands by scaling definitely improves the efficiency over the previous multiple-models approach. This approach also reduces the number of models involved in the prediction system and, in the analysis phase, allows data from different stands to be combined in a complementary system. It extends the discrete reference-height to a continuous reference-height through a simple but explicit multiplication and is therefore more functional. In principle, this algebraic adjustment approach is similar to some

---

D. Warnell School of Forest Resources, The University of Georgia, Athens, Georgia 30602, USA, Phone: (706) 542-8169

contemporary systems of site-tree height curves, and localization of models with the Kalman filter approach (Walters *et al.* 1991) could be considered a modern application of such a method.

Newer approaches to site-tree height modeling almost exclusively involve three and four dimensions by adding to basic height over age models additional explicit variables of site index (S, third dimension) and base age (Ab, fourth dimension). An early algebraic inclusion of S into simple anamorphic models was followed by increased model complexity necessary to describe height growth polymorphism and other desirable model characteristics. Some of these included: (1) curves through the origin, (2) variable asymptotes, and (3) equality of predicted height and S at base age.

Peschel (1938) and Prodan (1968) credit Spath in 1797, Hossfeld in 1822, and Smalian in 1937 with the first attempts to express height growth by mathematical equations. Today parameters for such equations are commonly approximated or estimated through linear, and more recently, non-linear regressions. With such equations becoming more and more complex, containing new added variables such as S and Ab, the generated curves, or rather multidimensional spaces, have brought about improvements in biological soundness such as polymorphism and variable asymptotes. With increasing sophistication in the analysis approaches used to determine model parameters, the model simulations become more exacting.

Bailey and Clutter (1974) introduced the concept of base-age invariance in which a height at any age may be predicted directly from any age-height pair without compromising consistency of the predictions. Base-age invariant models can be viewed as four-dimensional spaces that are continuous over all dimensions. The heights predicted with base-age invariant models are unaffected by arbitrary changes in base age. In their work, Bailey and Clutter (1974) applied a technique that has become know as the algebraic difference approach (ADA, see also Borders *et al.* 1984). Site models derived with this approach are mathematically sound and always compute consistent estimates.

At present, virtually all site index models are based on algebraic forms of the fixed or variable base-age formulations that can be either base-age specific, base-age invariant, or base-age variant. The different mathematical forms of these models have different implications for the model operational use in inventory projections.

MODEL FORMS AND FUNCTIONAL ASSUMPTIONS

The mathematical equations used in growth and yield modeling can be linear or non-linear. Linear models are less flexible and usually require more terms (or parameters) to satisfactorily explain the data. This may lead to model overparameterization and unreasonable predictions outside the range of the data on which the model is calibrated. Linear models with many parameters are likely to become atypical in shape and difficult to defend biologically. Non-linear models are more flexible, more likely to be biologically sound, and usually much better behaved outside of the data range (Pienaar and Turnbull 1973).

Peschel (1938), Prodan (1968), Ricker (1979), Cieszewski and Bella (1989, 1991b, 1994), Elfving and Kiviste (1997) and others give numerous examples of basic growth models and various site models used to model height in forestry. From the stand view of a model formulation, the site index models can be categorized as a fixed base age, base-age invariant, and base-age variant. These categories are described below.

Fixed Base-Age Models

Fixed base-age site index models denote models that predict height at any age as a function of this age and a site index at a fixed base age that is obtained from a direct height measurement at any age. These models can be unconstrained or constrained to define the site index as equal to height at the base age. It is important to recognize that the site index in the unconstrained S models does not define any height at any age. Assuming such a definition is one of the most prevalent misconceptions about S models of practitioners who might be using heights at base age as a known site index either in the model fitting or in computing model predictions.

There are many modifications of base models providing either anamorphic or polymorphic fixed base-age site index height models such as the modifications of the Chapman-Richards function by Hegyi (1981), Lundgren and Dolid (1970), Biging (1985), Ek (1971), and Payandeh (1974), and the modification of the logistic function by Monserud (1984).

Some of the modified models became so complicated in an attempt to obtain a better fit to the data that they became unsolvable for S as a function of a height and age. Since they require prior knowledge of S, usually calculated from an observed height at some age, separate models are developed for S as a function of the height at any age. Models for height and S that are derived separately are usually incompatible with their corresponding height models. Another problem is that some base-age specific models, e.g., all the above modifications of the Chapman-Richards and the logistic functions, generate curves that may not go through appropriate heights at their base ages. That is, they predict heights at base ages that are not equal to the site index used as a predictor variable. These and similar models can be conditioned to give site index as the predicted height when age is equal to base age, e.g., Burkhart and Tennant (1977), while analytically unsolvable models can be treated numerically by iterative search routines.

When the fixed base-age S models are simple enough to be solvable for S, they are in terms of predictions functionally equivalent to the base-age invariant models. A similar functional equivalency can be achieved with the fixed base-age S models that are not solvable for S but are applied with compatible numerical solutions for the S values.

Base-Age Invariant Models

Bailey and Clutter (1974) introduced the notion of Base-Age Invariance in the forestry literature. This concept has been defined as invariance of predictions and curves (the invariant) with respect to the selection of base age, i.e., not changing predictions for any selection of base ages within each site series. Base age is simply a common age value for all curves at which the heights on the curves represent site indices (or the reference heights) or initial conditions of the equation. If the curve is invariant, any such age-height point on a curve chosen as a reference unequivocally defines the very same curve. This is not true with the models listed above. Thus, they are not base-age invariant.

Two conditions must prevail for a model to be base-age invariant:
(1) the model must be represented in a base-age invariant algebraic form, and
(2) the model coefficients must be estimated in a way that avoids any influence of the choice of base age on the values of the model coefficients.

Using a base-age invariant algebraic form but base-age specific estimation will result in a base-age invariant equation with base-age specific coefficients. That is, it would not result in a base-age invariant model. Using a base-age specific algebraic form and base-age independent parameter estimation methods would result in a base-age specific equation with base-age invariant coefficients, e.g., Garcia (1983). A model like that of Garcia (1983) could just be solved for the site-specific coefficient (Bailey and Clutter 1974) and, with back substitution, converted to a totally base-age invariant model.

When a base-age dependent algebraic form is used, the achievement of a base-age invariant model is impossible. Clearly, if the coefficient estimation method was base-age invariant, i.e., if no base ages contributed to (or affected) the estimation of coefficients, the model could not possibly produce predictions governed by the base ages because no information about base-age influence on prediction would be acquired. In other words, the model predictions cannot be functionally changing with different selections of base ages unless such changes are defined in a multi-base-age-specific fitting of the model. Thus, the base-age variant models are neither base-age invariant in their forms nor are they base-age invariant in their coefficients. They are equivalencies of conglomerations of multiple base-age specific models with smooth and continuous changes between different base-age specific submodels. This seems to be what Goelz and Burk (1992) intended but mislabeled as base-age invariance.

The notion of base-age invariance is applicable only to models that can directly and consistently predict height at all ages from a single reference height at a single reference age, i.e., base age. Iterative models that predict only a fixed increment or height for each age cannot be base-age invariant because they do not use a single base age (selection of which could be an issue) nor do they directly predict all heights from any selection of a base age. Simply, if there are no multiple predictions of all heights from multiple individual selections of base ages, there is nothing that can be variant or invariant with respect to selection of the base ages. Thus, for example, the iterative model in Wang and Payandeh (1995) is neither base-age variant nor base-age invariant (just like it is neither tall nor short). It simply does not involve the relevance of this concept.

Furthermore, a model formulation is base-age invariant if and only if it analytically defines all heights as a function of any height with outcomes totally unaffected by any choices of base ages and without any use of other equations, numeric searches, programs, generators, guesses, or any other means. Models that require iterative numerical searches for estimation of arbitrary heights from inputs at any ages or for estimation of compatible site indexes are not base-age invariant. Clearly, if the existence of numerical approximations of a model solution was the only criterion for base-age invariance, then every base-age-specific model ever invented would be base-age invariant and the term would be meaningless.

Examples of base-age invariant models published since Bailey and Clutter (1974) include: Amaro *et al.* (1998), Borders *et al.* (1984), Borders *et al.* (1988), Begin and Schutz (1994), Cao *et al.* (1993, 1997), Cieszewski and Bella (1989, 1991a, 1993), Clutter *et al.* (1983), Clutter *et al.* (1984), DuPlat and Tran-Ha (1986), Elfving and Kiviste (1997), Lappi and Bailey (1988), McDill and Amateis (1992), Vicary *et al.* (1984), and Ramirez *et al.* (1987). Examples of different approaches to proper derivation of base-age invariant models besides Bailey and Clutter (1974) are in Amoro *et al.* (1998), Cieszewski and Bella (1989, 1994), Elfving and Kiviste (1997), and McDill and Amateis (1992).

Other forestry examples of development of true base-age invariant equations (not using this name) published before Bailey and Clutter (1974) are Bennett *et al.* (1959), Coile and Schumacher (1964), and Lenhart (1968, 1972).

Site index models are usually based on panel data (i.e., temporal and spatial attributes combined in the same measurements). Not all potentially base-age invariant models have been used for modeling panel data. In fields outside of forestry, examples of such equations and their proper derivations used for individual Y over X relationships may be found in the works of Schnute (1981) and Ratkowsky (1983, 1990).

Other equivalencies of base-age invariant equations in mathematics, physics, and other fields resulting from initial condition or boundary value solutions to differential equations or other difference equations have been in use since the early 16/17th century. For example, Johannes Kepler (1571-1630) formulated *Kepler's second law* relating to movement of planets, which may be expressed as $A(t_2) = A(t_1) + \frac{1}{2} h(t_2 - t_1)$ -a truly base-age invariant equation, and it can be used to fit panel data in forestry as, in fact, demonstrated in Bailey and Clutter (1974) where $A = Ln\ H$.

Begin and Schutz (1994) is a kind of standout. The authors develop a truly base-invariant model according to the definition in Bailey and Clutter (1974), but they appear to be unaware of the existence of that article and cite Goelz and Burk (1992), who they, in fact, do not follow. Furthermore, treatment of coefficients and fitting in Begin and Schutz (1994) mimics that of DuPlat (1986), who admittedly also follows Bailey and Clutter (1974).

Base-Age Variant Models

The base-age variant site index models are formulations that create curves that vary under different choices of base ages during the model applications. Examples of those models include Goelz and Burk (1992), Payandeh and Wang (1994, 1995), Huang (1994a,b), Huang *et al.* (1994), and Wang and Payandeh (1996).[1]

The base-age variant models are capable of creating similar inconsistencies as the fixed base-age site index models with incompatible S solutions. However, since the base-age variant models are using as input height at any age, they do not generate inconsistencies of the imput values, only output values. This is unlike the fixed-age S models with incompatible S solutions. The degree of the inconsistencies depends on the selection of sites and base ages.

SI MEASUREMENTS VS. S ESTIMATES

SI models require the knowledge of S for their use. This knowledge comes from various height measurements and at times from S estimates from other variables. It is clear that S estimate from other variables is an estimate, but it is not clear if it should be considered an estimate or a measurement when it is defined by a direct height measurement at an age different than the base age.

Site index can be considered either a measurement or an estimate depending on the mathematical form of the applied site index model and the treatment of the site index solution for a fixed base-age S model. In a simplest case of a variable base-age model, the measured reference height enters the model directly as the S at any given base age, and it is clearly a measurement. Any S at a fixed age, e.g., 50 years, predicted by this model can be considered an estimate, but it is irrelevant to the usage of this model or to its predictions that are strictly driven by the direct height measurement at any given age.

A similar case, though not as obvious, is a fixed base-age S model with a compatible S solution. In such models the height at any age enters the mathematical formula without any deviation from its actual value, and at the age of the measured reference height, which is the age of the model initiation, the model contains no error other than the one associated with the measurement. Furthermore, any imprecision of such model estimates results from the model infidelity rather than from the fact that S is estimated from a height at age different than the base age and that this estimation in turn results in a model input different from the actual measurement.

A special comment should be made about the fixed base-age S models that have compatible S solutions but are not conditioned to predict appropriate heights at the base age, such as Hegyi (1981), Lundgren and Dolid (1970), and Biging (1985). These models are just as consistent in predicting heights as the conditioned fixed base-age S models with compatible S solutions, and for all intents and purposes, the site indexes in these models should be considered measurements, not estimates. Unfortunately, these models mis-display the site indexes due to their sloppy formulations and may mislead a careful practitioner about the misgivings of the model S inputs. The part of the formula in these models that pretends to be the site index, e.g., S or SI, is really just a mathematical constant without any necessary associated meaning other than a necessity of an intermediate calculation. This intermediate calculation must be followed indiscriminately to the age of measured height even if the input height is measured at an age equal to the base age. However, as long as S in these models is computed as the intermediate step, the fixed base-age S models will compute consistent height estimations regardless of the age at which the input height is measured, and they will always be initiated exactly at this very height. Therefore, the inherent site index in these models is measurement, not estimate, despite the superficial appearance of the seemingly erroneous formulation.

---

[1] *Since expressing such relationships as equalities implies contradictions such as "1=0" a proper notation for them could be defined by replacing "=" signs with "(" or for a small range of t1 values they could be expressed correctly as approximates using "(."*

The only situation of site index applied as an estimate exists in applications of fixed base-age S models using incompatible site index prediction models. This is so because such applications result in initiating the height models at heights different from those measured and intended for the model input. Such applications disregard the basic principle of the S model being a family of height over age time-series trends, of which a unique trend is identified by a height measurement at any arbitrary age. Clearly, if a height at any age is used to identify a unique series, this height must belong to this series and no statistical considerations are relevant to this concept. Thus, in consideration of S models, treating S as an estimate that somehow needs to be statistically inferred from height and age measurements is a mistake resulting from a misunderstanding of those models and their function as merely a description of height over age trends across a range of productivity sites. Accordingly, statistical developments of the site index prediction models meant to predict the fixed base-age site indexes from heights at arbitrary ages are ill-founded and serve no other purpose than confusing the reader and discrediting the use of S models in the eyes of the general public. All S models should be used with compatible analytical or numerical S solutions. If an actual equation predicting S (from heights and ages) is practically necessary for a given S height over age model, it should be calibrated on this very model to be as compatible with it as possible. The compatibility between the two models is in this case the bottom line criteria, and for this reason it is wrong to calibrate such a model on the data. This compatibility is the only criterion because it is the height measurement that defines the series we seek—not some kind of other "mysterious" variable (like site index) that we might approximate or infer from the measurement. Consequently, in consideration of S models, the site index can be assumed an estimate only in situations of model misuse and misinterpretation. In all other uses of S models, the site index is either a measurement (variable base-age models) or a parameter of intermediate computations (fixed base-age models) serving a function equivalent to a measurement.

CONSISTENCIES OF INVENTORY PROJECTIONS

The consistencies of the inventory projections are examined for the above mentioned form of site index models, assuming the following four criteria of potential model uses:

(1) Computations of site index stability over time
(2) Predictions of heights at all ages from different base ages
(3) Predictions of heights at a harvest age using intermediate computation of S
(4) Predictions of heights at a harvest age directly from measured heights at different ages.

It is noted that the last point does not directly reflect inventory projections, but it indirectly affects them because site indexes are used in almost all growth and yield models as necessary input variables, thus affecting all computed growth and yield predictions.

Base-Age Invariant Models

Base-age invariant site index models report consistent heights regardless of the base ages used and always are consistent in correctly reporting the site indexes as equal to heights at base ages. When using these models, the site indexes calculated from generated height over age series are constant over time (fig. 1a). Regardless of what base age is used, the height over age patterns are always identical for any given site. Figure 1b shows four sets of curves for three sites. As a result of base-age invariance with respect to selection of base ages, all sets of curves on this graph are identical so it seemingly appears to represent only one set of curves.

Similarly, when computing heights at the harvest age of 150 years, the predictions are indifferent to the base age from which the harvestable height is computed. The heights at harvest age depend only on the productivity site and are indifferent to both the base age and the method of computation. When they are computed from site index that is computed from the measured height and age (fig. 1c), they are identical to the ones computed directly from the measured height and age (fig. 1d).

The base-age invariant models produce identical predictions regardless of which way they are used, and site indexes computed with these models are unaffected by age. Using any height age pair within a height over age series, these models define unequivocally the very same series.

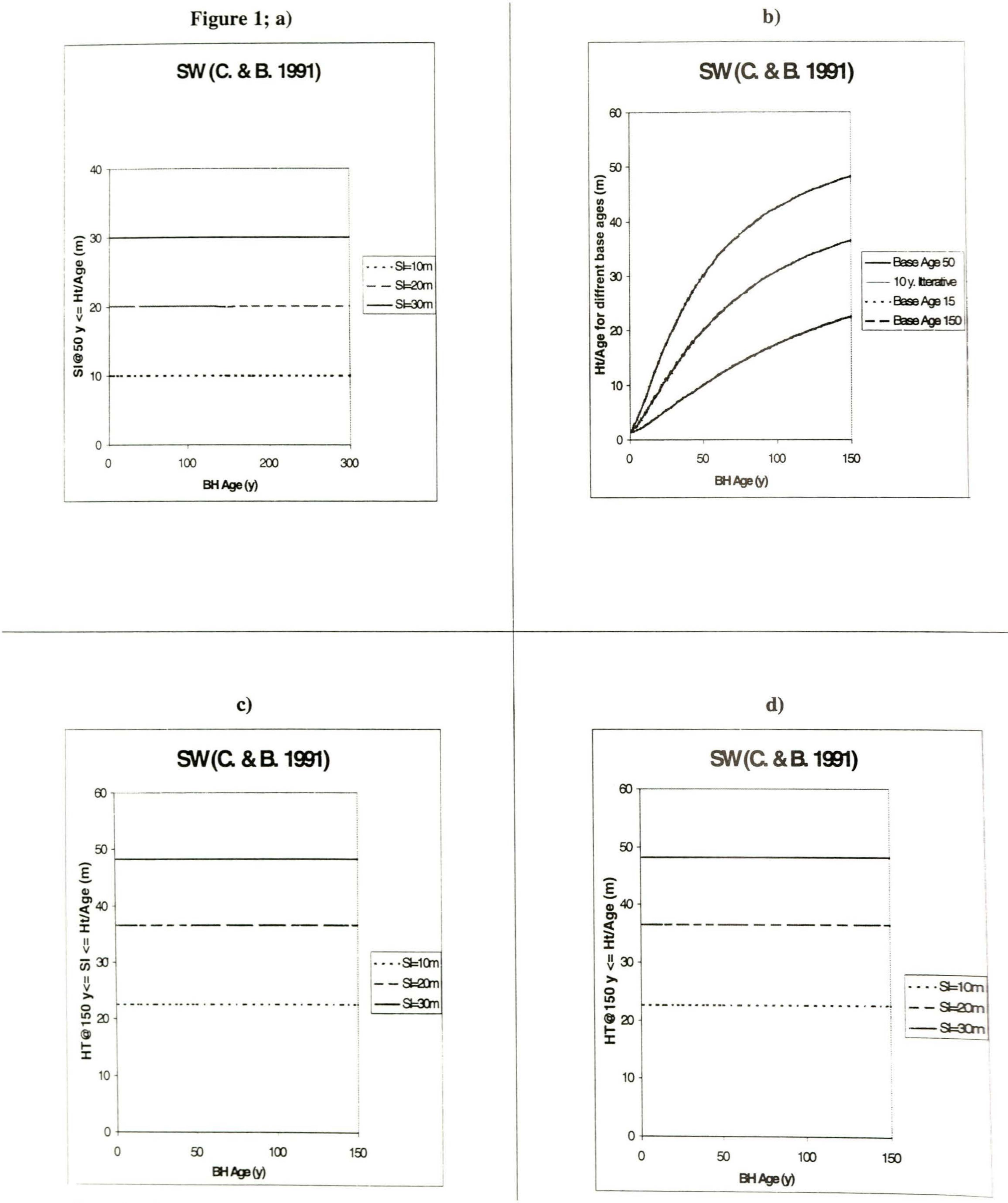


Figure 1.—*Base-age-invariant models for low, medium, and high sites: a) site index predictions unaffected by age of reference height; b) height predictions unaffected by selection of base age; c) predictions of height at harvesting age (computed with intermediate site index calculations) unaffected by age of reference height; and d) predictions of height at harvesting age (computed directly from reference height and age) unaffected by age of reference height.*

Fixed Base-Age S Models with Compatible S Solutions

When the fixed base-age S models are used consistently with intermediate S calculations, then even if they are unconstrained they should produce appropriate heights at any input age (including the S base age) equal to input heights at the input age. Of course, for the unconstrained models, S will be different than the H at base age, but this is not important because the curves are driven through appropriate input heights anyway and the site indexes are simply misreported while the height predictions are not affected by this misreporting.

Proper uses of those models with compatible S solutions will generate predictions that are similar to those from using base-age invariant models. The site indexes computed for different ages as well as heights at base age and at harvest age will be constant over the whole range of input ages. As a consequence of the stable site indexes, the height over age trends will be also consistent and invariant with respect to the selection of the input base ages in the model applications (fig. 2b). Similarly, the height at harvest age (fig. 2c) or any other age will be consistent and unaffected by the age of the input height measurement.

Unlike the case of base-age invariant models, there is a standing issue with the model ambiguity of the fixed base-age S models. The definition of site index, the method of model constraint, the methodology of model usage, the model parsimony, and the compatibility and methodology of obtaining site index solutions are just some of the problems of fixed base-age S models. It is probably these and similar associated dilemmas and misuses that contribute to a broad criticism of site index models and a broad public mistrust and disapproval of site index models in general.

Fixed Base-Age S Models with Incompatible S Solutions using S Estimates

Fixed base-age site index models used with incompatible S solutions compute predictions affected by different choices of base ages. The site indexes in these models are estimates because they are not a mere consequence of the model form transforming the height measurement into a point of reference; instead, they are statistical inferences based on isolated from the S model data interpretations. As a consequence, the site index estimates in these systems are inconsistent over different ages (fig. 3a). This means that the selections of growth series for inventory projections are ambiguous (fig. 1b,c) even though the heights over age series are consistent (fig. 1c).

Due to the change in site index with input age, any predictions of heights will be base-age dependent and will yield inconsistent values varying with different ages of height measurements (fig. 3c). This in turn may result in erroneous height predictions. In the example illustrated in figure 3d, the measured height at age 100 yields 41.4 m, which implies the site index of 25.1, which in turn predicts a height of 41.2 m at a harvest age of 150 years.

Base-Age Variant S Models with Variable Base-Age S Measurements

The base-age variant S models, e.g., Goelz and Burk (1992), Payandeh and Wang (1994, 1995), Huang (1994a, b), Huang *et al.* (1994), and Wang and Payandeh (1996), are the most inconsistent and ambiguous of all the models discussed, and their algebraic formulations are malformed and ill conditioned. According to these models:

(1) site indexes vary over time (fig. 4a);
(2) heights over age trends change with base ages (fig. 4b);
(3) heights at harvest age (fig. 4c and d) or any other age can be anything; and
(4) predictions are biased by different types of model usage (fig. 4b and c vs. d);

A more complete discussion of these models and their use go beyond the scope of this paper.

CONCLUSIONS

The consistency of model estimations in using self-referencing models depends on the type of model used. The highest consistency of model predictions and interpretations is expected from base-age invariant models with direct use of height age measurements for their input and lack of ambiguity about the model input vs. output interpretation.

Fixed base-age S models with adequate compatible S solutions in analytical or numerical forms alike can provide the equivalent of base-age invariant S model consistency in model predictions despite their ambiguity about usage and model interpretation. The misleading forms of these models suggesting a special role of S in the model interpretation are only superficial and can be ignored if a base-age invariant methodology for parameter estimation is used to calibrate these models (Bailey and Clutter 1974, Garcia 1983, DuPlat 1992).

Fixed base-age S models with incompatible S solutions developed separately from the height over age models produce inconsistent results that are varying predictions with different choices of base ages. The use of those models is ambiguous and unreliable in terms of inventory projections with no conclusive numbers to relay on. The ambiguity is in the future forecasting determination of the input heights (the input height is different from intended)

Figure 2; a)

b)

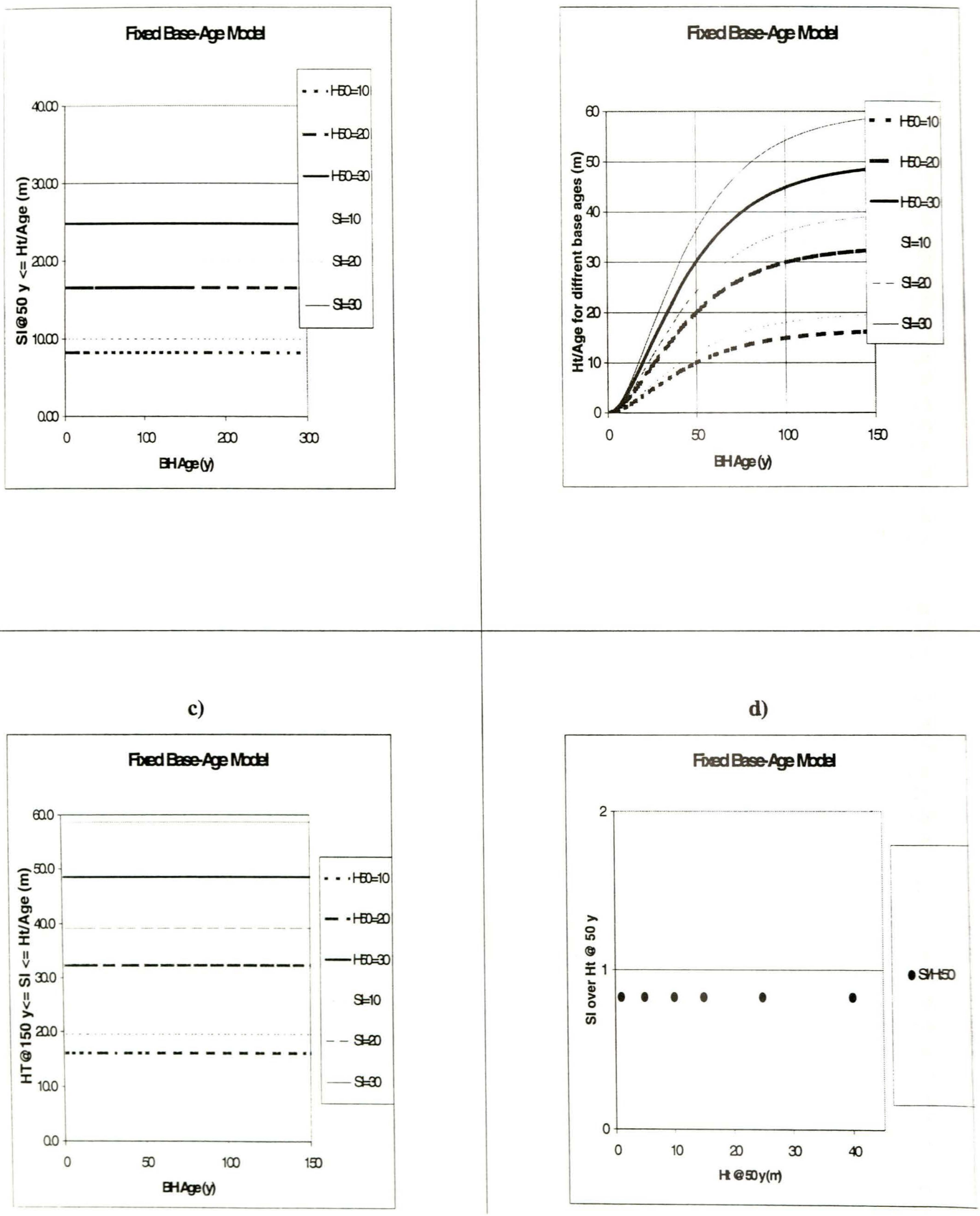


Figure 2.—*Unconstrained (hence the lack of consistency between the site indices and the predicted heights at base age) fixed-base-age site index models with compatible site index solutions for low, medium, and high sites: a) site index predictions unaffected by age of reference height; b) height predictions unaffected by selection of base age; c) predictions of height at harvesting age (computed with intermediate site index calculations) unaffected by age of reference height; and d) relative error in height predictions at harvesting age (computed directly from reference heights and ages) unaffected by age of reference height.*

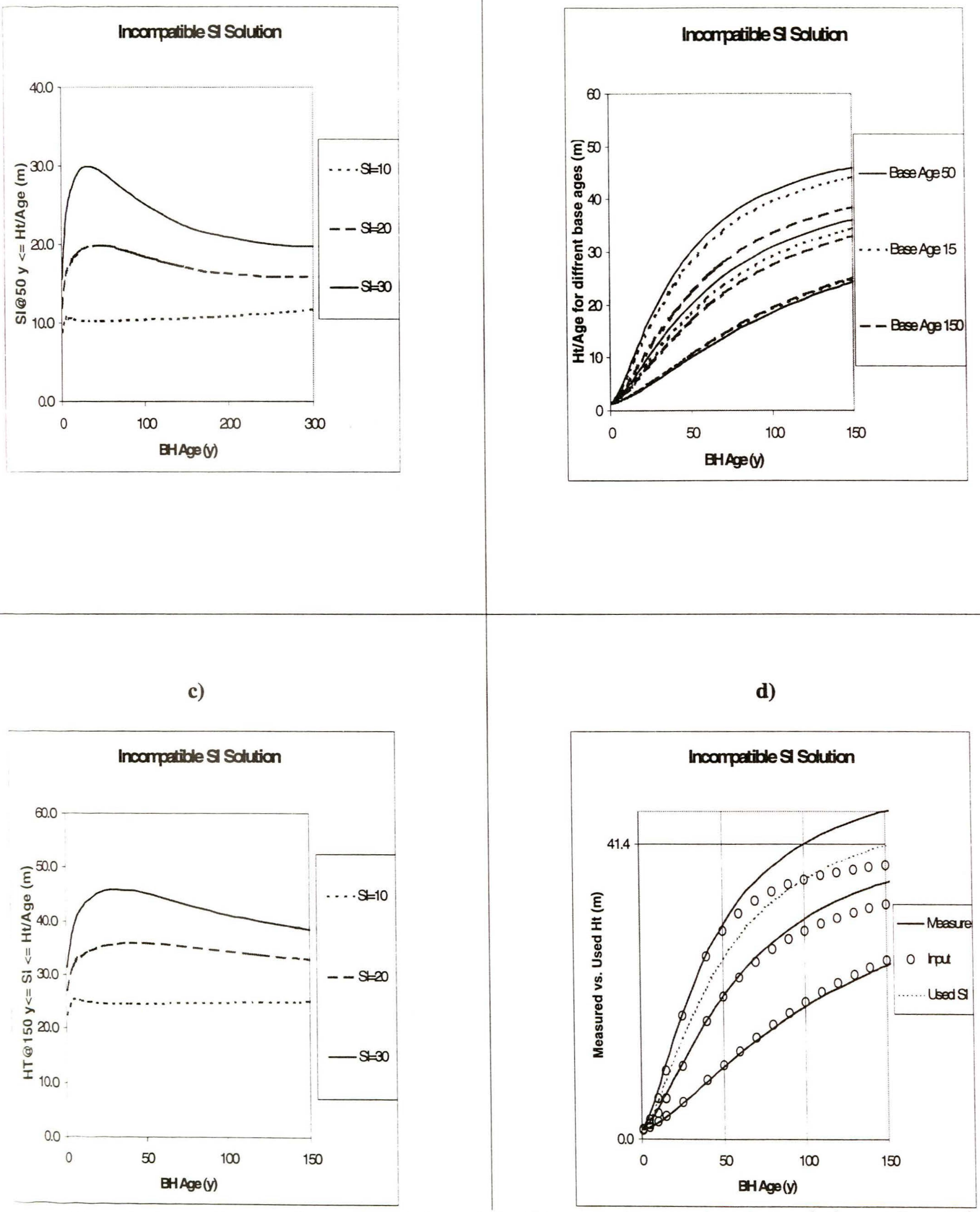


Figure 3; a)

b)

c)

d)

Figure 3.—*Constrained fixed-base-age site index models with incompatible site index solutions for low, medium, and high sites: a) site index predictions change with age of reference height; b) height predictions change with selection of base age; c) predictions of height at harvesting age (computed with intermediate site index calculations) change with age of reference height; and d) 25.1 m site index (predicted from 41.4 m height at age 100 yr) predicts 41.2 m height at age 150 yr.*

Figure 4; a) b) c) d)

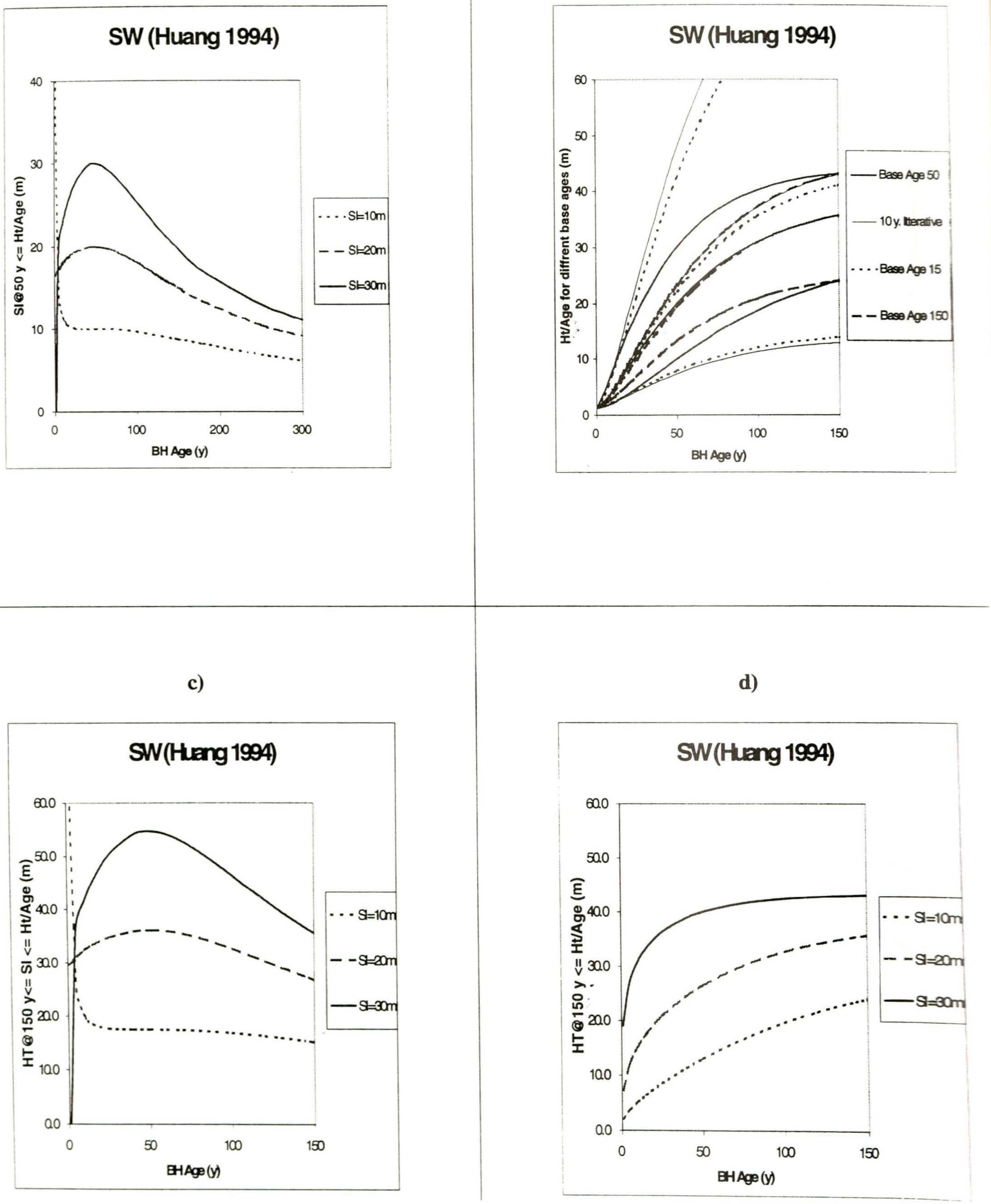


Figure 4.—*Base-age-variant models for low, medium, and high sites: a) site index predictions change with age of reference height; b) height predictions change with selection of base age; c) predictions of height at harvesting age (computed with intermediate site index calculations) change with age of reference height; and d) predictions of height at harvesting age (computed directly from reference height and age) change with the reference age.*

and in consistency of the S estimation as an attribute of growth (SI changing with age).

The base-age variant models (Goelz and Burk 1992; Payandeh and Wang 1994, 1995; Huang 1994a,b; Huang *et al.* 1994; and Wang and Payandeh 1996) are the most ambiguous in terms of their predictions and usage. Since these models maximize effects of the stochastic predictive variables, they are incompatible with their own predictions and cannot be used in the usual variety of common scenarios such as iterative simulations, and back and forth computations. They are inadequate for computation of S inputs into other models or even their own. The degree of this ambiguity varies with site and age selections. Typically it is most dramatic at the extremes of their values.

Inconsistency in site index estimations can result in major economical implications. For example, in forestry administration systems similar to those in British Columbia, a substantial portion of the land base might be taken out of sustainable constant yield calculations due to underestimation of S values in old-growth stands. This in turn would result in a substantial reduction of the AAC on false premises and would hurt the industry and provincial economy with implications for employment and revenues.

LITERATURE CITED

Amaro, A.; Reed, D.; Tome, M.; Themido, I. 1998. Modeling dominant height growth: Eucalyptus plantations in Portugal. Forest Science. 44(1): 37-46.

Bailey, R.L.; Clutter, J.L. 1974. Base-age invariant polymorphic site curves. Forest Science. 20: 155-159.

Begin, J.; Schutz, Jp. 1994. Estimation of total yield of Douglas-fir by means of incomplete growth series. Annals of Forest Science. 51(4): 345-355.

Bennett, F.A.; McGee, C.E.; Clutter, J.L. 1959. Yield of old-field slash pine plantations. Pap. SE-107. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station.

Biging, G.S. 1985. Improved estimates of site-index curves using a varying-parameter model. Forest Science. 31: 248-259.

Borders, B.E.; Bailey, R.L.; Ware, J.D. 1984. Slash pine site-index from a polymorphic model by joining (splining) nonpolynomial segments with an algebraic difference method. Forest Science. 30: 411-423.

Borders, B.E.; Bailey, R.L.; Clutter, M.L. 1988. Forest growth models: parameter estimation using real growth Series. P. 660667. In: Ek, A.R.; Shifley, S.R.; Burk, T.E., eds. Forest growth modeling and prediction. vol. 2. Proceedings, IUFRO conference. Gen. Tech. Rep. NC-120. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 1,149 p.

Burkhart, H.E.; Tennant, R.B. 1977. Site-index equations for Radiata pine in New Zealand. New Zealand Journal of Forest Science. 7-3: 408-416.

Cao, Q.V. 1993. Estimating coefficients of base-age-invariant site index equations. Canadian Journal of Forest Research. 23(11): 2343-2347.

Cao, Q.V.; Baldwin, V.C., Jr.; Lohrey, R.E. 1997. Site index curves for direct-seeded loblolly and longleaf pines in Louisiana. Northern Journal of Applied Forestry. 21(3): 134-138.

Chi, E.M.; Reinsel, G.C. 1989. Models for longitudinal data with random effects and AR(1) errors. Journal of the American Statistical Association. 84: 452-459.

Cieszewski, C.J.; Bella, I.E. 1989. Polymorphic height and site-index curves for lodgepole pine in Alberta. Canadian Journal of Forest Research. 19: 1151-1160.

Cieszewski, C.J.; Bella, I.E. 1991a. Polymorphic height and site index curves for the major tree species in Alberta. Edmonton, Alberta: Forestry Canada, Northwest Region, Northern Forestry Center, Forest Management Note. 51.

Cieszewski, C.J.; Bella, I.E. 1991b. Towards optimal design of nonlinear regression models. In: Rennolls, K.; Gertner, G., eds. The optimal design of forest experiments and forest surveys. Proceedings of a IUFRO S4.11 conference; 1991 September 10-14; London, UK: University of Greenwich.

Cieszewski, C.J.; Bella, I.E. 1993. Modeling density-related lodgepole pine height growth, using Czarnowski's stand dynamics theory. Canadian Journal of Forest Research. 23: 2499-2506.

Clutter, J.L.; Fortson, J.C.; Pienaar, L.V.; Brister, G.H.; Bailey, R.L. 1983. Timber management. New York: John Wiley and Sons, Inc. 333 p.

Clutter, J.L.; Harms, W.R.; Brister, G.H.; Reney, J.W. 1984. Stand structure and yields of site-prepared loblolly pine plantations in the lower coastal plain of the Carolinas, Georgia, and north Florida. Gen. Tech. Rep. SE-27. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 173 p.

Coile, T.S.; Schumacher, F.X. 1964. Soil-site relations, stand structure, and yields of slash and loblolly pine plantations in the Southern United States. Durham, NC: T.S. Coile Inc. 296 p.

DuPlat, P.; Tran-Ha, M. 1986. Modeles de Croissance en Hauteur Dominante pour le hetre, le sapin pectine et le pin sylvestre (dans le Massif de l'Aigoual). Document no 86.1. Office National de Forets. France.

Ek, A.R. 1971. A formula for white spruce site-index curves. For. Res. Notes 161. University of Wisconsin. 2 p.

Elfving, B.; Kiviste, A. 1997. Construction of site index equations for *Pinus sylvestris* L. using permanent plot data in Sweden. Forest Ecology Management. 98(2): 125-134.

Furnival, G.M.; Gregoire, T.G.; Valentine, H.T. 1990. An analysis of three methods for fitting site-index curves. Forest Science. 36: 464-469.

Garcia, O. 1983. A stochastic differential equation model for the height growth of forest stands. Biometrics. 39: 1059-1072.

Goelz, J.C.G.; Burk, T.E. 1992. Development of a well-behaved site index equation: Jack pine in north central Ontario. Canadian Journal of Forest Research. 22: 776-784.

Hegyi, F. 1981. Site index equations and curves for the major tree species in British Columbia. For. Inv. Rep. No. 1.

Huang, S. 1994a. Ecologically based reference-age invariant polymorphic height growth and site index curves for white spruce in Alberta. Tech. Rep. Pub. T/305. Edmonton, Alberta: Land and Forest Services, Alberta Environmental Protection.

Huang, S. 1994b. Ecologically based reference-age invariant polymorphic height growth and site index curves for major Alberta tree species: least squares fit statistics and residual plots. Tech. Rep. Pub. T/308. Edmonton, Alberta: Land and Forest Services, Alberta Environmental Protection.

Huang, S.; Titus, S.J.; Lakusta, T.W. 1994. Ecologically based site index curves and tables for major Alberta tree species. Tech. Rep. Pub. T/307. Edmonton, Alberta: Land and Forest Services, Alberta Environmental Protection.

Laird, N.M.; Ware, J.H. 1982. Random-effects models for longitudinal data. Biometrics. 38: 963-974.

Lappi, J.; Bailey, R.L. 1988. A height prediction model with random stand and tree parameters: an alternative to traditional site-index methods. Forest Science. 34-4: 907-927.

Lenhart, J.D. 1968. Yield of old-field loblolly pine plantations in the Georgia Piedmont. Athens, GA: University of Georgia, School of Forest Resources. Ph.D. thesis.

Lenhart, J.D. 1972. An alternative procedure for improving height/age data from stem analysis. Forest Science. 18: 332.

Lindstrom, J.L.; Bates, M.B. 1988. Newton-Raphson and EM algorithms for linear mixed effects models for repeated measures data. Journal of the American Statistical Association. 83: 1014-1022.

Lindstrom, J.L.; Bates, M.B. 1990. Nonlinear mixed effects models for repeated measures data. Biometrics. 46: 673-687.

Lundgren, A.L.; Dolid, W.A. 1970. Biological growth functions describing published site-index curves for lake states timber species. Res. Pap. NC-36. St. Paul, MN: U.S. Department of Agriculture, Forest Service.

McDill, M.E.; Amateis, R.L. 1992. Measuring forest site quality using the parameters of a dimensionally compatible height growth function. Forest Science. 38(2): 409-429.

Monserud, R.A. 1984. Height growth and site-index curves for inland Douglas-fir based on stem analysis data and forest habitat type. Forest Science. 30: 943-965.

Northway, S.M. 1985. Fitting site-index equations and other self-referencing functions. Forest Science. 31: 233-235.

Payandeh, B. 1974. Formulated site-index curves for major timber species in Ontario. Forest Science. 20: 143-144.

Payandeh, B.; Wang, Y. 1994. Relative accuracy of a new base-age invariant site index model. Forest Science. 40(2) 341-348.

Payandeh, B.; Wang, Y. 1995. Preliminary site index equations for three planted species in northern Ontario. Northern Journal of Applied Forestry. 12(2): 57-63.

Peschel, W. 1938. Die mathematischen Methoden zur Herleitung der Wachstumsgesetze von Baum und Bestand und die Ergebnisse ihrer Anwendung. Tharandter Forstl. Jahrb. 89: 169-247.

Pienaar, L.V.; Turnbull, K.J. 1973. The Chapman-Richards generalization of Von Bertallanfy's growth model for basal area growth and yield in even-aged stands. Forest Science. 19: 2-22.

Prodan, M. 1968. Forest biometrics. English ed. Oxford: Pergamon Press. p. 447.

Racine-Poon, A. 1985. Bayesian approach to nonlinear random effects models. Biometrics. 41: 1015-1023.

Ramirez, M.H.; Bailey, R.L.; Borders, B.E. 1987. Some implications of the algebraic difference approach for developing growth models. In: Proceedings, IUFRO forest growth modelling symposium; 1987 August 24-28; Minneapolis, MN: 731-738.

Ratkowsky, D.A. 1983. Nonlinear regression modeling: a unified practical approach. New York: Marcel Dekker.

Ratkowsky, D.A. 1990. Handbook of nonlinear regression models. New York: Marcel Dekker.

Ricker, W.E. 1979. Growth rates and models. Chapter 11, Fish Physiology. 8. New York, NY: Academic Press.

Schnute, J. 1981. A versatile growth model with statistically stable parameters. Canadian Journal of Fish Aquatic Science. 38(9): 1128-1140.

Stiratelli, R.; Laird, N.; Ware, J.H. 1984. Random-effects models for serial observations with binary response. Biometrics. 40: 961-971.

Vicary, B.P.; Brann, T.B.; Griffin, R.H. 1984. Base-age invariant polymorphic site index curves for even-aged stands of spruce and balsam fir in Maine. Maine Aes Bulletin. (802): 1-33.

Walters, D.K.; Burkhart, H.E.; Reynolds, M.R., Jr.; Gregoire, T.G. 1991. A kalman filter approach to localizing height-age equations. Forest Science. 37(6): 1526-1537.

Wang, Y.H.; Payandeh, B. 1995. A base-age invariant site index model for aspen stands in north central Ontario. Forest Ecology and Management. 74(2-3): 207-211.

Wang, Y.; Payandeh, B. 1996. Evaluating a dimensionally compatible height growth modeling approach. The Forestry Chronicle. 72(6): 647-650.

A Review of Methods for Updating Forest Monitoring System Estimates

Hector Franco-Lopez, Alan R. Ek, and Andrew P. Robinson

Abstract.—Intensifying interest in forests and the development of new monitoring technologies have induced major changes in forest monitoring systems in the last few years, including major revisions in the methods used for updating. This paper describes the methods available for projecting stand- and plot-level information, emphasizing advantages and disadvantages, and the subsequent use of the updated information in constructing new estimates. Research directions that might lead to improving the updating process are also discussed.

OVERVIEW

Lund (1993) defined forest monitoring as the periodic measurements or observations of selected physical, chemical, and biological parameters for establishing baselines for detecting and quantifying changes in the forest over time, and to evaluate management and silvicultural alternatives (including harvesting). In practice, a forest monitoring system (FMS) is typically a strategic survey designed to check on or to keep track of the condition of the forest in a region, providing up-to-date information for the development of policies and programs for protection, management, and forest utilization.

The usefulness of broad-scale forest inventory information is determined by its frequency, accuracy, and subject matter (Sheffield 1987). The most generally requested improvements associated with these factors are more frequent inventories (up-to-date information), greater spatial sampling intensities to provide accurate local estimation, improved subject matter coverage (incorporation of new variables and improved measures of change), and increased information availability. Another concern with the information provided by FMS's is the reduction in length of the inventory reporting cycle. There is substantial demand for more current data (4- to 6-year cycles instead of the typical 10- to 15-year cycle).

Smith (1990) defines the term "update" as an estimate of the current forest condition derived by modeling the dynamic change in a forest from a known time and condition in the past. Update estimates are developed because full-scale inventories are too expensive to be conducted as information is needed; by updating, information needs often can be met at substantial cost savings over remeasurement. In addition, updating can enhance the quality of regional and national assessments since inventories varying in age can be projected to a common year.

Several authors (e.g., Ek 1990 and Smith 1990) define the following as desirable attributes of an updating technique:

1. The update should include revision of all plot and tree variables that might have changed since the last measurement;
2. Input and output of an updating system would necessarily need to be consistent and compatible with inventory data definitions and availability. This ensures that the same software can be used to summarize updated and remeasured records;
3. The level of resolution of the updating system needs to be capable of long-term projections as well as short-term updates;
4. The updating system should be calibrated for all stand conditions, and calibration data should be representative of the type of stands to which the data will be applied. This condition is essential to get unbiased updates; and
5. The system should meet the requirements of a range of users, from sophisticated users that require individual tree records to those seeking only aggregated inventory statistics.

Since updating can be defined as projecting forest inventory information to an specific date, we have two basic questions to answer: (1) How do we project tree and/or plot information to a specific date? and (2) How do we use the updated information to construct estimates? The following sections review and summarize the available methods for addressing these two questions.

PLOT INFORMATION PROJECTION

Two groups of plot-level variables are of concern in updating. The first group is comprised of the categorical variables, such as land use, cover type, stand size and density class, and disturbance history. The second group includes continuous variables, such as volume, basal area, and number of trees per acre.

Research Assistant and CONACyT fellow, Professor, and Research Assistant, respectively, Department of Forest Resources, University of Minnesota, St. Paul, MN, USA.

Updating Categorical Variables

In large-area FMS's, there may be substantial land-use and forest-type changes over the monitoring cycle. Classification or stratification update is the basic ingredient for area estimation. Teuber (1990) stated that classification updating has been practically restricted to the identification and quantification, through remote sensing, of important area changes resulting from timber harvesting, regeneration, land-use conversion, and natural disturbance. There are two basic approaches to the use of remote sensing for updating. The first compares two independent estimates of area (without an identification process in which you can say which specific plots have changed). The second approach consists of registering imagery obtained at two or more points in time and comparing them to determine specific plots or areas that have changed (digital change detection). Poso (1993) proposed a postclassification approach based on field measurements, avoiding all preclassifications and using measurable tree and stand variables. An advantage of his approach is that a classification function based on field measurements is constructed and can be used to update tree, plot, and stand information. However, this approach assumes a much more intensive inventory than those normally conducted in North America.

Other approaches to updating classifications include the use of econometric techniques to update area statistics by forest type, and the Kalman filter (Czaplewski 1990). In the first case, exogenous data on harvesting and planting are used to model classification changes. In the second, the Kalman filter approach combines a series of forest inventories, updates, or monitoring estimates, using a model of expected change in forest condition over time, to predict cover changes from land-use conversions, regeneration, and harvest.

The seemingly straightforward approach of estimating area by class from remote sensing leaves little room for updating detailed statistics, because classification is imprecise and even small changes in remote sensing classification affect area estimations in a very significant way. Thus, even though classification or stratification is the basic ingredient for estimation of totals (volume, growth, and removals), the lack of improvements in the precision of the approaches we use to update remote sensing classification has stalled this approach.

As a more direct solution to classification and updates, considerable progress has been made in Northern Europe. Tomppo (1991) and Tokola *et al.* (1996) applied the k-nearest neighbors (kNN) method for classification problems and used it to produce localized estimates and maps in the national forest inventory of Finland. This "pixelwise" approach of kNN is used to propagate field sample plot classification and volume information to all pixels in a region. The method is based upon the spectral distance between the pixels having known field data and the pixels to be classified. A distance function (e.g., Euclidean) $d_{(i)p}$ is computed in the feature space from the pixel p to each pixel i (on satellite imagery) whose ground truth is known from sample plots. The estimate of the ground variable m for the subject pixel is then given by:

$$\hat{m}_p = \sum_{j=1}^{k} w_{(j),p} m_{(j),p}$$

where $w_{(j),p}$ are related distance calculated weights and $m_{(j),p}$ are the values of the variable m in the k closest pixels in the spectral space to the pixel p. Classifications are imputed as the modal or "nearest" class. Variations of this approach have also been tested with success in the Swedish national forest inventory (Nilsson 1997).

Updating Continuous Variables

Burkhart (1993) described how inventories are commonly updated through the application of growth and yield models. Many different approaches to modeling growth and yield have been taken, ranging from techniques that use individual trees as the basic projection unit to methods that use only overall plot or stand summary data.

Stand-Level Models

In plot- or stand-level models, variables such as plot age, site index, basal area and/or number of trees per unit of area are used to update aggregate stand basal area, number of trees, and volume. Since volume distribution by tree species and size class is difficult to project directly, disaggregation or allocation models may be needed to provide that detail.

Individual Tree Models

Updating using this kind of model involves simulation of the growth of each tree and then aggregation to provide estimates of stand growth and yield (i.e., we obtain the estimates by summing individual tree characteristics and multiplying by plot, and other expansion factors). Such models typically consist of three basic tree submodels: (1) diameter growth, (2) height growth, and (3) mortality.

Individual tree models can be divided into distance independent and distant dependent types (Munro 1974). Distance independent models do not consider individual tree locations on plots in developing the basic submodel estimates of tree growth and mortality. Further, they typically use a plot level measure of competition (such as basal area) in estimating tree level growth. Distance dependent models typically use a competition measure based on the size and distance of competitors.

When individual tree models satisfy the desirable attributes of an updating technique, they provide the following advantages over other methods:

1. They provide updated information about stand dynamics and structure, including the distribution of tree and stand variables by classes. Through the analysis of these characteristics, the user obtains information about more complex issues (cover type change, succession, biodiversity, etc.).
2. They can be used for updating tree categorical variables (i.e., log grade, health, or condition, etc.).
3. An updated plot has the same information as a field measured plot, so the same database management system and software can be used for inventory analysis and compilation as well as update.
4. They supply a wide range of information for analysis by sophisticated and non-traditional users.

Individual tree models have been the most widely used technique for forest inventory updating. Individual tree models such as STEMS (Stand and Tree Evaluation and Modeling System) and PROGNOSIS emerged in the mid-1970's and have become the choice for many Forest Inventory and Analysis (FIA) applications. The use of STEMS to project undisturbed plots in the FIA unit of the USDA Forest Service's North Central Research Station is a typical example of the use of individual tree models for updating FMS's (Birdsey and Schreuder 1992).

As interest in updating FMS statistics through the use of models has increased, the following improvements have been commonly requested:

- **Variance information**. Most projection systems provide predictions of different forest attributes, but usually they do not provide estimates of the variance of the predictions. This information is crucial in the updating procedure to assess the precision of predictions, to evaluate the general performance of the models, and to calculate confidence intervals for the estimates. Given the usual complexity of the models used in forestry, analytical calculations of prediction variances are impossible to get. Mowrer (1988) used Monte Carlo simulation to provide a relative estimate of the errors propagated over repeated measurements by two models. This is a relatively straightforward procedure that propagates only errors in regression predictor variables and their cross products. Under Mowrer's approach, the variance associated with the regression coefficient errors was ignored. Gertner (1987) used the error propagation method as an alternative to obtain estimates of precision of predictions made with a forest model. He concluded that although the estimates were slightly biased, this method provides a mean for calculating the variance in a computationally efficient manner.

- **Accuracy and detail**. The estimation for early stages of stand development is commonly weak. Improvements are needed in the form of including ingrowth and/or full regeneration estimation. Only a few models contain components that will predict regeneration conditions after harvesting. The principal factor limiting the widespread development of regeneration models is the imprecision in estimating postharvest conditions. Ek *et al*. (1997) suggested that a regeneration model should predict stand conditions for a given stand at some time during the first two decades after harvest. It is important to improve early-stage estimation for credible long-term projection and to achieve credibility among users with ecological interests (Ek 1990).

- **Sensitivity to local conditions**. It is a very frequent practice to extend the results or to use a model outside of the region in which it was initially calibrated. But doing so typically introduces bias in estimations. Although a re-calibration of the model (calculating new regional coefficients) to compensate for local conditions is in order, the use of model adjustments is frequently found in the literature (Smith 1983). Adjustment factors attempt to correct for the difference between a predicted value and the real field measured value. This approach is popular because of its simplicity, but its usefulness does not last long. Also, because it pools all local factors together, there is no way to get a good explanation of their separate influence on the predictions. There are two possible solutions to improve local sensitivity. The first solution is to identify the factors driving the local responses (weather, disturbances, etc.), assess the specific weight of each factor among the dependent variables, and then develop new models using them as predictors. The second possibility is to improve the model re-calibration procedure for models.

Alternative methods to the use of regression models for updating FMS's are beginning to appear in the forestry literature. Simple and multiple imputation, as proposed by Rubin (1987), is a statistical technique designed to handle missing data. This technique allows statistical analysis using the same software used for complete databases. Simple imputation consists of filling in a single value for each missing value from an underlying model and database. A model in this context can be as simple as the tabular representation of the data corresponding to different strata. The single value imputed does not reflect sampling variability about the actual value or additional uncertainty when more than one underlying model is being entertained. However, it does retain the variability in the data and simplifies data processing. Multiple imputation consists of filling each value m times with randomly selected data from an underlying model and database. The resulting m data sets are analyzed separately using the method for complete data. These *m* intermediate results are then pooled into a final result.

Van Deusen (1997) discussed alternative methods for the analysis of annual, interpenetrating, systematic samples. He concluded that any analysis appropriate for a complete data set is appropriate for imputed, simulated-complete data sets, whether the imputed values might come from regression models or by matching measured with unmeasured sample units.

The few examples of the use of imputation in forestry can all be catalogued as simple imputation. Poso (1978) described the use of the grouping method in the Finnish national forest inventory. In this method, photo plots were interpreted for all the important attributes that show sufficient correlation between photo and field estimates. The photo plots were then grouped, and from each group one photo plot was randomly drawn and measured in the field. The information from this plot was then propagated to all photo plots belonging to the respective homogeneous group. Since a single value from an underlying model (the strata) was imputed for each one of the photo plots, this constitutes a single imputation example. Moeur and Stage (1995) briefly described another single imputation example in the Swedish FMS. In this case, an unsampled (in the field) first-phase unit is paired with a randomly selected second-phase (field sampled) unit from the same stratum. Ek *et al.* (1997) developed and tested imputation models to estimate postharvest forest stand characteristics. The imputation models were developed by tabular analysis of different stand regeneration conditions. They recommended cover type, age, and site index based models that provided realistic and detailed species and size class descriptions for regenerated stands.

"Plotwise" and "treewise" kNN methods have also been proposed as an alternative to regression techniques for updating continuous variables. In this approach, kNN is used to propagate plot or tree field information to unmeasured units. Haara *et al.* (1997) compared the kNN with Weibull parameter models for basal area diameter distribution estimation in a "plotwise" approach. They determined that the accuracy of the Weibull function estimation was better than that of kNN, but the latter reproduced the covariance structure of the attributes best.

Korhonen and Kangas (1997) used the "treewise" kNN approach for generalizing sample tree data. They found diameter, location (y and x coordinates), mean age of growing stock, basal area of growing stock, and mean diameter of growing stock to be good predictors for stem volume and sample tree characteristics (height and age).

Moeur and Stage (1995) described the "most similar neighbor" inference procedure, which chooses the most similar plot from the set of plots detailed to act as stand-in. The stand-in is chosen on the basis of similarity measures that summarize the multivariate relationships between a set of low resolution indicator attributes and detailed second-phase sample attributes.

ESTIMATION

Estimation involves use of the available data to actually construct forest monitoring systems estimates. In the cases described below, current observations, updates of earlier observations, and older observations that have not been updated are all considered as available data.

Estimation "as is"

This is the simplest estimation case. It consists of using the updated plot and/or tree data directly, relying entirely on the projection technique employed (i.e., using updates "as is," as field data). However, because the techniques we employ to project information may not be calibrated for all conditions, or simply because they are biased or imprecise, we typically seek more refinement in estimation.

The estimators described next can be considered members of a family of estimators commonly called "composite estimators." The general approach consists of combining two or more alternative estimators of a single quantity, i.e., weighting them to find a good estimator in some well-defined sense (Burk *et al.* 1982). Examples include the following:

Moving Average

This method is biased and usually considered an *ad hoc* procedure. It consists simply of taking the last n-year's observations and averaging them. The underlying assumption is that no major changes occur during those n-years. Optional weighting (inverse to time since last measurement or inverse to the variance) is sometimes considered. This estimator does not use projected plot information, but it is attractive for FMS's where some percentage of plots are measured each year. If area estimates, including stratification by area or condition, are precise and accurate and conducted in a consistent manner over time, then for many stratum variables, a moving average of stratum means can be simple and effective.

Double Sampling for Regression

The main assumption behind the standard double sampling with regression estimators is that a linear relationship exists between the variable of interest and a covariate. Examples of viable covariates are previous observations, or projected or imputed values substituted for observations. When projections are used, ratio or regression models describing the observed versus predicted relationship may then be used to adjust model outputs directly. These same adjustments may be used to adjust outputs for projections into the future. The same observed versus predicted data may also be used to recalibrate the model or to adjust certain parameters. However, with complex non-linear models, iterative derivation of parameter adjustments may be necessary to reach agreement between observed and predicted values. The North Central FIA unit uses the growth model enhanced, two-phase sample design described by Hansen (1990), using model projections as a covariate. In this particular case, the standard error for the projection model is unknown and the differences between the projected and measured values are used to compute model adjustment factors.

Gertner (1987) indicated that this method of calculating the variances is limited when projected observations are used as covariates. The disadvantage is that an independent set of remeasured plots is needed for calibration purposes, and this independent set must match the characteristics of the plots being projected in order for the variances to be correctly estimated.

The utility of this estimator depends on the strength of the relationship between the variate and covariate. An advantage of this estimator is that its statistical properties are well known; i.e., it provides valid error estimates. It is also a versatile method since several different attributes can be used as covariates in the same inventory. For example, consider adjusting the projected observations using ancillary data (e.g., local weather disturbances during the updating period). With this approach, many useful variables not usually considered in the projection models can be introduced very easily.

The Kalman Filter

This is a composite estimator that combines two independent estimates at a time, each of which is weighted inversely proportional to its variance (Czaplewski 1990). One of the independent estimates is a current estimate or monitoring measurement, and the other is a previous estimate that is updated for expected changes over time using a deterministic prediction model. The variance for this updated estimate includes the effects of (1) errors in the previous forest inventory that are propagated over time and (2) model prediction errors between previous and current estimates. Errors in this composite estimator are typically less than errors in either of the prior estimates alone. However, as with many other update techniques, there is a need for accurate models providing prediction errors. Descriptions of this technique can be found in the forestry literature (Czaplewski 1990, Dixon and Howitt 1979).

FUTURE DIRECTIONS

The above discussion describes the difficulties in the seemingly simple task of updating forest inventories. This review further highlights the areas needing research if updating is to be improved. The most important research needs are summarized below.

- Explore the use of imputation (single and multiple), especially the kNN method, as an alternative to regression in updating large-scale FMS's. In particular, research should consider improving local area updates, including those for classifications, growth estimation, and mapping of diverse forest inventory variables.
- Develop a set of procedures to generalize the use of computationally intensive methods for calculating the variance of the estimations from complex projection systems.
- Revisit re-calibration for local adjustment. This is an everyday problem in updating. This research would include identifying the factors driving local responses in models (weather, disturbances, etc.). This kind of analysis would be helpful in the variable selection procedure for constructing new models, for re-calibration for local adjustment, and for better understanding of the factors behind forest growth prediction.
- Given the expansion in methods for updating tree and plot information (single and multiple imputation), revisit the estimation procedures and evaluate them under these new circumstances.

ACKNOWLEDGMENT

The authors gratefully acknowledge helpful reviews by Thomas E. Burk, Professor, University of Minnesota, St. Paul, MN, USA; and Mark H. Hansen, Research Forester, USDA Forest Service, North Central Research Station, St. Paul, MN, USA. Research supported by the College of Natural Resources and the Agricultural Experiment Station, University of Minnesota.

LITERATURE CITED

Birdsey, R.A.; Schreuder, H.T. 1992. An overview of forest inventory and analysis estimation procedures in the Eastern United States: with an emphasis on the components of change. Gen. Tech. Rep. RM-214. Fort

Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 11 p.

Burk, T.E.; Hansen, M.H.; Ek, A.R. 1982. Combining sources of information for improved in-place inventory statistics. In: In-place resource inventories: principles and practices, proceedings of a national workshop; 1981 August 9-14; Orono, ME. SAF Publ. 82-02. Bethesda, MD: Society of American Foresters: 413-442.

Burkhart, H.E. 1993. Tree and stand models in forest inventory. In: Proceedings of Ilvessalo symposium on national forest inventories; 1992 August 17-21; Helsinki, Finland. Res. Pap. 444. Helsinki, Finland: The Finnish Forest Research Institute: 165-170.

Czaplewski, R.L. 1990. Combining inventories of land cover and forest resources with prediction models and remotely sensed data. In: Global natural resource monitoring and assessment: preparing for the 21st century: proceedings of the international conference and workshop; 1989 September 24-30; Venice, Italy. American Society for Photogrammetry and Remote Sensing. 3: 1079-1089.

Czaplewski, R.L. 1990. Kalman filter to update forest cover estimates. In: State of the art methodology of forest inventory: a symposium proceedings; 1989 July 30-August 15; Syracuse, NY. Gen. Tech. Rep. PNW-263. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 457-465.

Dixon, B.L.; Howitt, R.E. 1979. Continuous forest inventory using a linear filter. Forest Science. 25(4): 675-689.

Ek, A.R. 1990. Interfacing forest inventory with growth and yield models. In: State of the art methodology of forest inventory: a symposium proceedings; 1989 July 30-August 15; Syracuse, NY. Gen. Tech. Rep. PNW-263. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 415-419.

Ek, A.R.; Robinson, A.P.; Radtke, P.J.; Walters, D.K. 1997. Development and testing of regeneration imputation models for forests in Minnesota. Forest Ecology and Management. 94(1-3): 129-140.

Gertner, G. 1987. Approximating precision in simulation projections: an efficient alternative to Monte Carlo methods. Forest Science. 33(1): 230-239.

Haara, A.; Maltamo, M.; Tokola, T. 1997. The k-nearest neighbour method for estimating basal-area diameter distribution. Scandinavian Journal of Forest Research. 12: 200-208.

Hansen, M.H. 1990. A comprehensive sampling system for forest inventory based on a individual tree growth model. St. Paul, MN: Department of Forest Resources, University of Minnesota. 256 p. Ph.D. dissertation.

Korhonen, K.T.; Kangas, A. 1997. Application of nearest-neighbour regression for generalizing sample tree information. Scandinavian Journal of Forest Research. 12(1): 97-101.

Lund, H.G. 1993. Sampling designs for national forest inventories. In: Proceedings of Ilvessalo symposium on national forest inventories; 1992 August 17-21; Helsinki, Finland. Res. Pap. 444. Helsinki, Finland: The Finnish Forest Research Institute: 17-25.

Moeur, M.; Stage, A.R. 1995. Most similar neighbor - an improved sampling inference procedure for natural resource planning. Forest Science. 41(2): 337-359.

Mowrer, H.T. 1988. A Monte Carlo comparison of propagated error for two types of growth models. In: Forest growth modeling and prediction: proceedings of the IUFRO conference; 1987 August 23-27; Minneapolis, MN. SAF Publ. 87.12. Bethesda, MD: Society of American Foresters. 2: 778-785.

Munro, D.D. 1974. Forest growth models - a prognosis. In: Growth models for tree and stand simulation: proceedings of 1973 IUFRO meeting, working party S4.01-4; Stockholm, Sweden: Royal College of Forestry Research Notes. 30: 7-21 .

Nilsson, M. 1997. Estimation of forest variables using satellite image data and airborne lidar. Umeå, Sweden: Swedish University of Agricultural Sciences. 31 p. Ph.D. dissertation.

Poso, S. 1978. National forest inventory in northern Finland. In: National forest inventory joint meeting of IUFRO groups: S4.02 forest resource inventory and S4.04 forest management planning and managerial economics; 1978 June 18-26; Bucharest, Romania. Bucharest, Romania: IUFRO: 378-385.

Poso, S. 1993. Forest classification based on sampling and measurements. In: Proceedings of Ilvessalo symposium on national forest inventories; 1992 August 17-21; Helsinki, Finland. Res. Pap. 444. Helsinki, Finland: The Finnish Forest Research Institute: 255-259.

Rubin, D.B. 1987. Multiple imputation for nonresponse in surveys. New York: John Wiley and Sons. 258 p.

Sheffield, R.M. 1987. Advancing the usefulness of forest surveys. In: Forests, the world, and the profession: proceedings of the 1986 Society of American Foresters national convention; 1986 October 5-8; Birmingham, AL. SAF Publ. 87.02. Bethesda, MD: Society of American Foresters: 321-324.

Smith, W.B. 1983. Adjusting the STEMS regional forest growth model to improve local predictions. Res. Note NC-297. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 5 p.

Smith, W.B. 1990. Inventory updates: overview of the North Central experience. In: State of the art methodology of forest inventory: a symposium proceedings; 1989 July 30-August 15; Syracuse, NY. Gen. Tech. Rep. PNW-263. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 442-448.

Teuber, K.B. 1990. Remote sensing techniques for updating forest inventories. In: State of the art methodology of forest inventory: a symposium proceedings; 1989 July 30-August 15; Syracuse, NY. Gen. Tech. Rep. PNW-263. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 436-441.

Tokola, T.; Pitkänen, J.; Partinen, S.; Muinonen, E. 1996. Point accuracy of a non-parametric method in estimation of forest characteristics with different satellite materials. International Journal of Remote Sensing. 17(12): 2333-2351.

Tomppo, E. 1991. Satellite image-based national forest inventory of Finland. International Archives of Photogrammetry and Remote Sensing. 28(7-1): 419-424.

Van Deusen, P.C. 1997. Annual forest inventory statistical concepts with emphasis on multiple imputation. Canadian Journal of Forest Research. 27(3): 379-384.

Assessing Uncertainty in Mechanistic Models

Edwin J. Green, David W. MacFarlane, and Harry T. Valentine

Abstract.—Concern over potential global change has led to increased interest in the use of mechanistic models for predicting forest growth. The rationale for this interest is that empirical models may be of limited usefulness if environmental conditions change. Intuitively, we expect that mechanistic models, grounded as far as possible in an understanding of the biology of tree growth, may be more useful in an altered environment. Unfortunately, such models often produce only point estimates, with no associated credible or confidence intervals. The Bayesian synthesis (BSyn) method provides a solution to this dilemma. We present a summary of the BSyn, and the results of an application of BSyn to PipeStem, a mechanistic model of forest growth calibrated for loblolly pine.

There has recently been a great deal of interest in characterizing the uncertainty associated with mechanistic models. Such models are not constructed from data in the way usual stochastic models are, and hence the common measures of uncertainty are not applicable. In this paper, we demonstrate the Bayesian synthesis method, first proposed by Raftery *et al.* (1995), for developing interval estimates with associated probability statements. We will use a variant of Raftery *et al.*'s original method to obtain predictions from PipeStem, a mechanistic model of forest stand growth.

PIPESTEM

The mechanistic model PipeStem describes the carbon balance and growth of an even-aged mono-specific stand on an annual basis (Valentine 1988, 1990; Valentine *et al.* 1997). The version we used was calibrated for loblolly pine. The mathematical model consists of 16 differential equations and additional ancillary functions. The differential equations completely describe the dynamic properties of a single model stand. The state variables that characterize the model stand ordinarily are initialized with measurements from a real stand that has aged 1 or more years since planting. Simultaneous numerical integration of the differential equations provides values of the state variables at any subsequent point in time, and these values serve as predictions for the real stand.

The growth rate of the model stand is defined as the difference between rates of production and loss of dry matter. Dry matter is measured in units of carbon *C*, and the rate of growth per unit land area is measured in units of *C/ha/year*. The rate of production of dry matter is defined as the difference between the rate of production of *C* substrate and the consumption of *C* substrate through maintenance and constructive respiration. These metabolic rates also have dimensions with units of *C/ha/year*.

Dry matter is divided into foliar, feeder-roots, and woody components. The proportion of *C* substrate allocated to the production of dry matter of each component is constrained to keep the morphological dimensions of the model stand in accord with pipe model theory (Shinozaki *et al.* 1964a,b). Losses of dry matter result from the turnover of foliage and feeder-roots, the death and self-pruning of branches associated with crown rise, and the death of trees associated with self-thinning.

In addition to the information about the carbon balance and production and loss of dry matter, PipeStem also furnishes total basal area (m^2/ha), average tree height (*m*), dominant tree height (*m*), average height to the base of a live crown (*m*), and tree density (*stems/ha*) on an annual timestep. Estimates or measurement of these four variables (ordinarily obtained from a real stand aged 1 year or more) suffice to initialize the PipeStem model.

Valentine *et al.* (1997) modeled the growth of loblolly pine stands at three sites in Virginia and one site in North Carolina. These areas were chosen because they are the locations of sample plots for the Virginia Tech Loblolly Pine Growth and Yield Research Cooperative, and the data from the sample plots could be used to evaluate the predictions from PipeStem. Predictions from the model matched observed data well.

In this study, we use a version of PipeStem that includes a routine that allows the user to specify the site index (average height of dominant trees at 25 years of age) of the stand under study. The total number of model parameters in this version of PipeStem is 24. Users must specify values for all 24 parameters, and then the model produces predictions according to the specified parameter values.

Professor and Graduate Assistant, Rutgers University, New Brunswick, NJ, USA; and Research Forester, USDA Forest Service, Northeastern Research Station, Durham, NH, USA, respectively.

BAYESIAN SYNTHESIS

Raftery *et al.* (1995) developed the Bayesian synthesis (BSYN) method to characterize uncertainty in mechanistic models. The basic approach is to use *all* available information to generate a joint premodel distribution on all model inputs (θ) and model outputs (ϕ). In the spirit of Bayesian analysis, this distribution should reflect as closely as possible the investigator's state of knowledge regarding both θ and ϕ *before* running the model (knowledge gained from the model may not be included or it would eventually be used twice). In fact, as we will see, the premodel distribution will often be a Bayesian posterior distribution. The mechanistic model is then used to translate the joint premodel distribution to a joint postmodel distribution on θ and ϕ.

Mathematically, the model consists of a mapping from θ to $\Phi(\theta)$, where $\Phi(\theta)$ is a submanifold in (ϕ-space, i.e., the model connects particular θ values with particular associated ϕ values. Now, let $p(\theta, \phi)$ represent the joint premodel distribution of θ and ϕ, and let $\pi(\theta, \phi)$ be the joint postmodel distribution. In BSYN, we assume the model is correct. This leads to:

$$\begin{aligned}\pi(\theta,\phi) &\propto p(\theta, (\Phi(\theta)) \text{ if } \phi = \Phi(\theta),\\ &\propto 0 \text{ otherwise.}\end{aligned}$$

The essential idea of BSYN is that the postmodel distribution is proportional to the premodel distribution for any values of θ and ϕ that are connected by the model. Other combinations of θ and ϕ are impossible according to the model, and hence are assigned postmodel probabilities of 0. Inference about ϕ or θ or any function of ϕ and/or θ is based on $\pi(\theta, \phi)$. The joint postmodel distribution can be marginalized to obtain a postmodel distribution of any quantity of interest. Interval estimates with valid posterior probability statements are available from the marginalized posterior distributions. For instance, if we let $\pi_\phi(\phi)$ denote the marginal postmodel distribution of ϕ, then the postmodel probability that ϕ is in some interval I is simply

$$\text{Prob}(\phi \: \varepsilon \: I) = \int_I \pi_\phi(\phi)\, d\phi.$$

Note that BSYN yields postmodel distributions not only of the model outputs (ϕ), but also of the model inputs (θ). The latter may prove helpful in future modeling efforts. For more details, consult Raftery *et al.* (1995) (including discussion and rejoinder).

Unfortunately, the original BSYN method suffered from Borel's paradox (Wolpert 1995). Essentially, this means that the results were not invariant to re-parametrization of the model. Givens and Bravington (1995) demonstrated that this is probably not cause for great alarm, but nevertheless it is bothersome. Raftery, Poole, and Givens (1996) (hereafter referred to as RPG) demonstrated that the root problem is a basic incoherence in the BSYN method, which had heretofore gone unnoticed. The problem may be stated as follows: the user specifies premodel distributions on the model inputs and outputs. In essence, the model is a transformation from θ to ϕ. Hence the model and premodel distributions of the inputs provide an *implied* premodel distribution on the outputs. Of course, the implied distribution will not be identical to the specified premodel distribution on the outputs. Hence the incoherence: two different *prior* distributions for the same quantity.

Fortunately, the Borel paradox may be avoided. As mentioned earlier, the joint premodel distribution represents all that is known about θ and ϕ exclusive of the model. This knowledge must have been gained either subjectively or from data. Hence it is appropriate to consider a general situation where information on θ or ϕ or both is represented by a traditional Bayesian subjective prior distribution and/or a likelihood based on whatever data are available. We will also assume that our premodel information on θ and ϕ is from independent sources, although not strictly necessary, as are our data (this will be discussed further in the Application section). Then the joint premodel distribution may be thought of as composed of four parts: two likelihoods and two priors, i.e.,

$$p(\theta, \phi) \propto q_\theta(\theta)\; L_\theta(\theta)\; q_\phi(\phi)\; L_\phi(\phi),$$

where $p(\theta, \phi)$ is the joint premodel distribution; $q_\theta(\theta)$ and $q_\phi(\phi)$ are premodel prior distributions on θ and ϕ, respectively; and $L_\theta(\theta)$ and $L_\phi(\phi)$ are likelihoods for θ and ϕ, respectively. Since likelihoods are known to be invariant to transformation (e.g., see Schweder and Hjort 1996), the incoherence must arise from the premodel prior distributions.

RPG and Givens and Roback (1997, hereafter referred to as GR) suggested a solution to the Borel paradox: pool the implied premodel distribution with the specified premodel distribution. For example, it is easy to find (or draw an arbitrarily large sample from) $q^p_\phi(\phi)$. This could be done by drawing a large sample for θ from $q_\theta(\theta)$. For each sampled observation, run the model to obtain the associated value of ϕ. The collection of ϕ's would then constitute a sample from $q^i_\theta(\phi)$. Importance sampling (see, for example, Rubin 1988) could then be used to select a sample from $q^p_\phi(\phi)$. Then BSYN could be used to derive $\pi_\phi(\phi)$, the postmodel distribution for ϕ.

Unfortunately, unless the model is 1:1, the postmodel distribution for θ is not immediately available from $\pi_\phi(\phi)$ because numerous points in θ-space may map onto the same point in ϕ-space. Hence, while we might be able to approximate the postmodel probability of some point, say, ϕ_i, it is not readily apparent how this information might be used to obtain postmodel probabilities for all the θ_j's that might have led to ϕ_i.

Raftery and Poole (1997) and Poole and Raftery (1998), hereafter referred to as RP and PR, respectively, developed the "full pooling" method for pooling the stated and implied priors on both the inputs and outputs, resulting in samples from $\pi_\theta(\theta)$ and $\pi_\phi(\phi)$, the postmodel distributions of θ *and* ϕ, respectively. See Green *et al.* (1998) for more details.

APPLICATION

PIPESTEM is calibrated for loblolly pine. Given initial stand conditions (site quality, average diameter, height, height to the live crown, number of stems per hectare, and stand age), the model projects the growth of the stand over time. Among the outputs produced by the model are basal area *(m^2/ha)* *(B)*, average stand height *(m)* *(H)*, and number of stems per hectare *(N)*. We used PIPESTEM to simulate the growth of a model loblolly pine stand on the Upper Coastal Plain of Virginia.

Spacing Trial Data

We used the Virginia Tech Spacing Trial data, maintained by the Virginia Tech Loblolly Pine Growth and Yield Research Cooperative. These data include three replications of a number of spacings. Measurements available include average stand height, basal area, and number of stems per hectare. We arbitrarily assumed our model stand was planted at location 3 (Roanoke Rapids, VA). Data from plots at this location were used to compute $L_\phi(\phi)$, the likelihood for the outputs. We did not specify a likelihood of the inputs, since we had no data to base one on. In essence, this means we assumed a constant likelihood for θ.

Premodel Distribution

Likelihood for Model Outputs

Four of the spacings in the Spacing Trial data yielded identical planting densities of 2,242 *stems/ha*. Hence we chose this as our planting density. At the time of this research, the latest data available were for age 12; therefore, we used age 12 data. The likelihood was assumed to be a three-dimensional normal distribution, and the 12 observations (three replications, four spacings) on basal area per hectare, average stand height, and number of stems per hectare were assumed to be independent realizations from this distribution. The mean basal area, height, and number of stems on these 12 plots were 31.5 *m^2/ha*, 10.9 *m*, and 2,101.3 *stems/ha*, respectively.

Prior Distribution on Model Inputs

In Bayesian Synthesis, the premodel prior distributions on the inputs, $q_\theta(\theta)$, should reflect all that is known about their feasible values. Consequently, we undertook the arduous task of researching each of the 24 inputs for PIPESTEM. The results of this study are contained in MacFarlane *et al.* (1998). For brevity, we will summarize the findings here.

We assumed the inputs were premodel independent. We recognized that this was unlikely to be true, but we were unable to specify reasonable prior covariances. Hence we decided to allow the model and available data to induce covariances in the postmodel distributions (in fact, one of the virtues of Bayesian analysis is that such covariances are available at the end of the procedure). Note that assuming prior independence may actually be viewed as a *conservative* procedure. Imagine the prior distribution in two dimensions, and for simplicity, assume they have the same scale. If the two parameters are independent, then the prior distribution is represented graphically by a circle. In contrast, if we specify an *a priori* correlation, then the prior distribution would be an ellipse contained within the circle. Hence the prior independence assumption actually allows one to consider more combinations of the two parameters than would be included if *a prior* dependence structure was specified.

For 19 of the parameters, we were able to specify prior means and variances. We used normal priors for these parameters. For two others, z_w and z_r, (see Valentine *et al.* 1997 or MacFarlane *et al.* 1998 for a complete listing of the PIPESTEM parameters and their interpretations) we were able to specify upper and lower bounds in addition to means and standard deviations. Hence, rather than using unbounded normal densities for these parameters, we chose to use beta densities. The beta density parameters were computed from the bounds, means, and standard deviations using the method described in Johnson and Kotz (1970, p. 44).

For the final three parameters (ρ, μ_1, and μ_2) our premodel prior distributions were uniform. We could find no published information on these three parameters. Hence we made liberal guesses about the minimum and maximum values, and specified the distributions to be flat in between.

Prior Distribution on Model Outputs

We obtained a site index of 23.4 *m* (base age 25) for location 3 from the Amateis *et al.* (1984) Coastal Plain site index equation. With this site index and the planting density, we derived prior distributions on three of the model outputs (basal area per hectare, average stand height, and number of stems per hectare) at age 12 with the aid of four common growth and yield models (Bailey *et al.* 1985, Amateis *et al.* 1984, Clutter *et al.* 1984, and Hafley *et al.* 1982). Unfortunately, it is not common for model developers to provide sufficient information to develop variance estimates. Hence we assumed a normal prior distribution on the outputs with a mean equal to the average of the predictions from the four models. For the covariance matrix, we used the maximum likelihood estimate from observations on these variables from plots planted at densities of 2,242 *stems/ha* at locations 1, 2, and 4 in the Spacing Trial data.

Model Stand Specification

In all runs of PIPESTEM, we initialized our stand at 2,242 *stems/ha* on land with a site index of 23.4 *m*. The initial (age 1) average diameter and height were specified to be equal to the averages calculated from the plots planted at 2,242 *stems/ha* at location 3 (1.12 *cm* and 0.41 *m*, respectively). Initial average height to the base of the live crown was arbitrarily specified to be 0.1 m.

Details of Bayesian Synthesis for PIPESTEM

We used the full pooling algorithm of Raftery and Poole to generate a sample of size 5000 from $\pi_\theta(\theta)$. Note that the sample from $\pi_\theta(\theta)$ may be thought of as a sample of model trajectories. Thus, although $\pi_\phi(\phi)$ is a sample from the postmodel distribution of ϕ at age 12, we can easily obtain postmodel distributions for ϕ at *any* age by running the model to the desired age for each combination of inputs in the sample from $\pi_\theta(\theta)$.

RESULTS

Histograms from the postmodel distributions of B, H, and N at ages 12 and 50 are presented in figure 1. With these samples it is possible to construct valid credible intervals. For example, in table 1 we present the mean, and the 2.5 and 97.5 percentiles for the samples in figure 1. The percentiles may be regarded as end points of approximate 95 percent credible intervals.

Several of the histograms and/or smoothed densities suggest bimodal distributions. The skew in the posterior

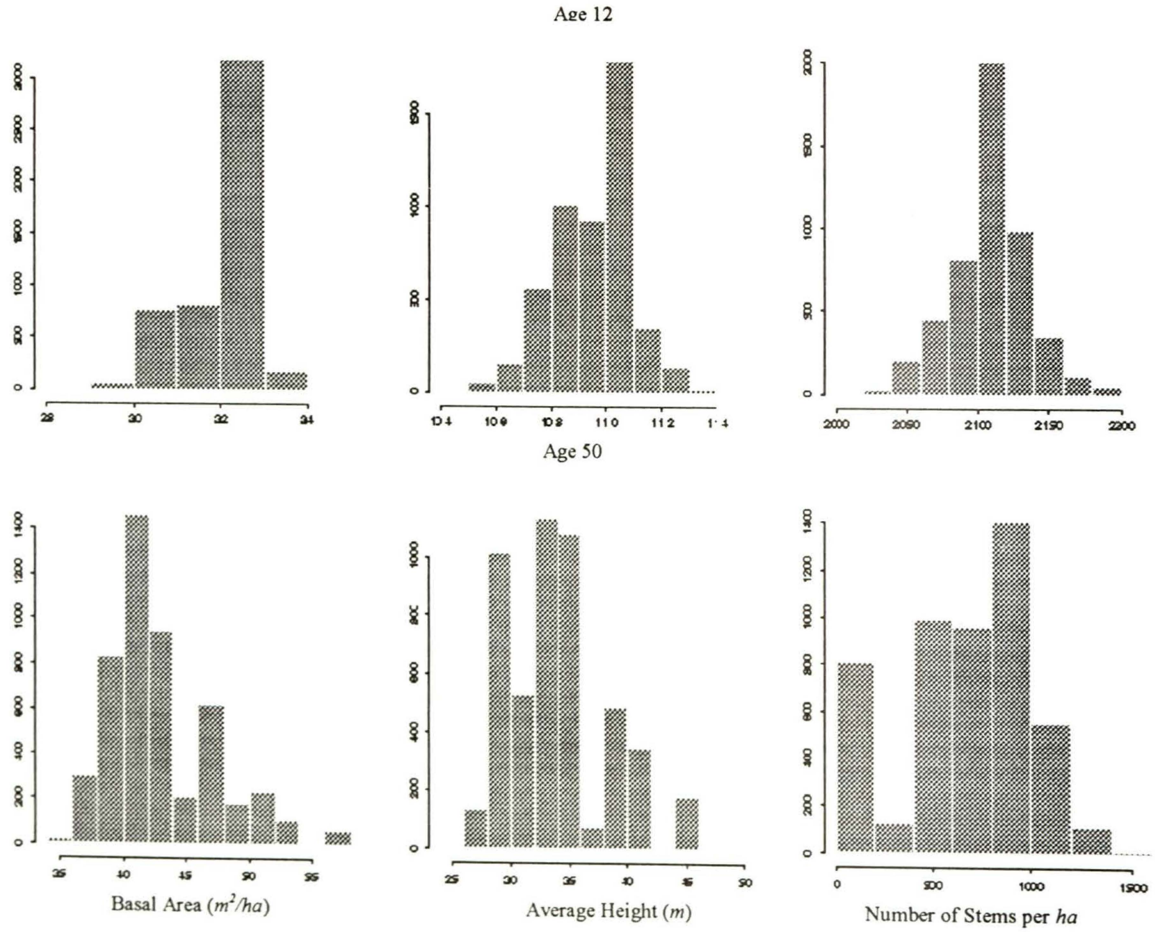


Figure 1.—*Histograms of samples from marginal posterior distribution for basal area (m^2/ha), average height (m), and number of stems per ha, at ages 12 and 50.*

Table 1.—*Means and approximate 95 percent credible intervals from posterior distributions*

Attribute	Mean	Lower limit (2.5 percentile)	Upper limit (97.5 percentile)
B (*m*^{2}*/ha*), age 12	31.9	30.1	33.2
B (*m*^{2}*/ha*), age 50	43.1	36.9	53.8
H (*m*), age 12	11.0	10.7	11.2
H (*m*), age 50	34.1	27.8	45.2
N (*stems/ha*), age 12	2,108	2,057	2,174
N (*stems/ha*), age 50	678	37	1,231

densities for B and H seems to have reversed between ages 12 and 50. Another noteworthy outcome is that while the specified prior mean for B of 31.6 *m*^{2}*/ha* was near the center of the age 12 posterior density, the specified prior values for H (12.6 *m*) and N (1942.4 *stems/ha*) do not appear to be plausible values according to the age 12 posterior densities. On the other hand, the observed means from location 3, which entered through the likelihood (31.5 *m*^{2}*/ha*, 10.9 *m*, 2,101.3 *stems/ha*), all appear to be very reasonable values according to figure 1. This is usual in Bayesian analysis; given a relatively vague prior, the posterior is ordinarily strongly influenced by the data.

The posterior density for number of stems at age 50 is surprising. Of the 5,000 observations in the age 50 sample, 11 percent had fewer than 100 *stems/ha*. This indicates that about one-tenth of the time we can expect very poor survival. Commonly used yield tables predict somewhat greater survival. For instance, the survival model Bailey *et al.* (1985) predicts survival of 335 *stems/ha* at age 50. However, growth and yield models usually are based on data from much younger stands (loblolly pine stands tend to be harvested well before age 50), and published studies show remarkable variation in predicted numbers of surviving stems per unit area (Burkhart *et al.* 1981). Long-term studies with many replications would be required to determine whether our results are reasonable.

More results, including analysis of the influence of the likelihood on ϕ, and examination of the posterior distribution of θ, are included in Green *et al.* (1998).

CONCLUSION

BSYN is a promising technique for generating posterior distributions and/or interval estimates for the outputs from mechanistic models. Unlike other methods of quantifying uncertainty in mechanistic models, BSYN incorporates all the information available to the user about the inputs and outputs of the model, in addition to the model itself. The end result is a joint posterior distribution of the model inputs and outputs, which may be used to make valid inferences about any of the input or output parameters, or any mathematical function of them.

ACKNOWLEDGMENTS

This work was supported by National Science Foundation grant #DEB-9602201, a grant from the USDA Forest Service Northern Global Change Program, and New Jersey Agricultural Experiment Station funds. We thank R.L. Amateis and H.E. Burkhart for data contributions to this study, R.L. Bailey and M.A. Buford for help in assembling growth and yield model information, and A.E. Raftery and G.H. Givens for helpful discussions on Bayesian Synthesis.

LITERATURE CITED

Amateis, R.L.; Burkhart, H.E.; Knoebel, B.R.; Sprinz, P.T. 1984. Yields and size class distributions for unthinned loblolly pine plantations on cutover site-prepared lands. Publ. FWS-2-84. Virginia Polytechnic Institute and State University. 69 p.

Bailey, R.L.; Grider, G.E.; Rheney, J.W.; Pienaar, L.V. 1985. Stand structure and yields for site-prepared loblolly pine plantations in the Piedmont and Upper Coastal Plain of Alabama, Georgia, and South Carolina. Res. Bull. 328. University of Georgia, College Agricultural Experiment Station. 118 p.

Burkhart, H.E.; Cao, Q.V.; Ware, K.D. 1981. A comparison of growth and yield prediction models for loblolly pine. Publ. FWS-2-81.Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources. 23 p.

Clutter, J.L.; Brister, W.L.; Rheney, J.H. 1984. Stand structure and yields of site-prepared loblolly pine plantations in the lower Coastal Plain of the Carolinas, Georgia, and North Florida. Gen. Tech. Rep. SE-27. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 173 p.

Givens, G.H.; Bravington, M.V. 1995. Borel's paradox and sensitivity analysis. Pap. SC/47/AS15 presented to IWC Scientific Committee. May 1995.

Givens, G.H.; Roback, P.J. 1997. Logarithmic pooling of priors linked by a deterministic simulation model. Tech. Rep. 97-21. Colorado State University, Department of Statistics. 19 p.

Green, E.J.; MacFarlane, D.W.; Valentine, H.T. 1998. Assessing uncertainty in a stand growth model by Bayesian synthesis. Manuscript submitted to Forest Science.

Hafley, W.L.; Smith, W.D.; Buford, M.A. 1982. A new yield prediction model for unthinned loblolly pine in plantations. Tech. Rep. 1. North Carolina State University, School of Forest Research, Bioeconomical Modeling Project. 65 p.

Johnson, N.L.; Kotz, S. 1970. Continuous univariate distributions - 2. New York, NY: John Wiley and Sons. 306 p.

MacFarlane, D.W.; Green, E.J.; Valentine, H.T. 1998. Parameter distribution estimation for a stand-level carbon balance model for loblolly pine. Manuscript in preparation.

Poole, D.; Raftery, A.E.. 1998. Assessment of the Bering-Chukchi-Beaufort Seas stock of Bowhead whales using Bayesian and full pooling Bayesian synthesis methods. Paper presented to the IWC Scientific Committee. April 1998.

Raftery, A.E.; Givens, G.H.; Zeh, J.E. 1995. Inference from a deterministic population dynamics model for Bowhead whales. JASA 90: 402-442, with discussion and rejoinder.

Raftery, A.E.; Poole, D.; Givens, G.H. 1996. The Bayesian synthesis assessment method: resolving the Borel paradox and comparing the backwards and forwards variants. Pap. SC/48/AS16 presented to the IWC Scientific Committee. June 1996.

Raftery, A.E.; Poole, D. 1997. Bayesian synthesis assessment methodology for Bowhead whales. Pap. SC/49/AS5 presented to the IWC Scientific Committee. September 1997.

Rubin, D.B. 1988. Using the SIR algorithm to simulate posterior distributions. In: Bernardo, J.M.; *et al.*, eds. Bayesian Statistics 3. Oxford, UK: Clarendon Press: 395-402.

Schweder, T.; Hjort, N.L. 1996. Bayesian synthesis or likelihood synthesis? What does the Borel paradox say? Report of the International Whale. Commission. 46: 475-480.

Shinozaki, K.; Yoda, K.; Hozumi, K.; Kira, T. 1964a. A quantitative analysis of plant form: the pipe model theory. I. Basic analyses. Japan Journal of Ecology. 14: 97-105.

Shinozaki, K.; Yoda, K.; Hozumi, K.; Kira, T. 1964b. A quantitative analysis of plant form: the pipe model theory. II. Further evidence of the theory and its application in forest ecology. Japan Journal of Ecology. 14: 133-139.

Thornley, J.H.M. 1970. Respiration, growth and maintenance in plants. Nature. 227: 304-305.

Thornley, J.H.M. 1971. Energy, respiration and growth in plants. Annals of Botany. 25: 721-728.

Thornley, J.H.M. 1976. Mathematical models in plant physiology. London: Academic Press.

Valentine, H.T. 1988. A carbon-balance model of stand growth: a derivation employing pipe-model theory and the self-thinning rule. Annals of Botany. 62: 389-396.

Valentine, H.T. 1990. A carbon-balance model of tree growth with a pipe-model framework. In: Dixon, R.K.; *et al.*, eds. Process modeling of forest growth responses to environmental stress. Portland, OR: Timber Press: 33-40.

Valentine, H.T.; Gregoire, T.G.; Burkhart, H.E.; Hollinger, D.Y. 1997. Pipestem: a stand-level model of carbon allocation and growth, calibrated for loblolly pine. Canadian Journal of Forest Research. 27: 817-830.

Wolpert, R.L. 1995. Comment on "Interference from a deterministic population dynamics model for Bowhead whales, by Raftery, A.E.; Givens, G.H.; Zeh, J.E. 1995.JASA 90: 402-442, with discussion and rejoinder.

The AFIS Tree Growth Model for Updating Annual Forest Inventories in Minnesota

Margaret R. Holdaway

Abstract.—As the Forest Service moves towards annual inventories, states may use model predictions of growth to update unmeasured plots. A tree growth model (AFIS) based on the scaled Weibull function and using the average-adjusted model form is presented. Annual diameter growth for four species was modeled using undisturbed plots from Minnesota's Aspen-Birch and Northern Pine Inventory Units. On the validation database, the AFIS model showed increased precision over the recalibrated STEMS model by 5 percent for diameter predictions and 8 percent for stand basal area predictions. The average-adjusted model form has a number of desirable features.

The mission of the Forest Inventory and Analysis (FIA) program is to conduct periodic inventories of U.S. forestlands to furnish updated information about the resource. To provide more precise and timely forest inventory information than produced with the present FIA design, Congress has mandated that the USDA Forest Service move to annual inventories on a 5- to 7-year cycle. In the north central region, a part of the new inventory procedure is to replace the Stand and Tree Evaluation and Modeling System (STEMS) with a new model to better update unmeasured inventory plots.

Currently FIA inventories use variable-radius plots. Since this sampling design is not optimal for growth modeling, substantial bias and variability may be introduced by the sampling procedure. However, an improved model form may increase the accuracy and precision of growth estimates on inventory data. Further, it is important that the models be calibrated from the same data and sampling scheme that the model will be applied to. First, the STEMS tree growth model is recalibrated on FIA data to evaluate the effect of modeling the same model form on FIA data as opposed to non-inventory data (Lessard 2000). Second, I evaluate a new model form calibrated on the same FIA data used in the recalibration of STEMS. Third, these models are analyzed with respect to the uncertainty of their predictions (McRoberts *et al.* 2000).

In this paper I present a new individual tree growth model called AFIS (Annual Forest Inventory System). The objectives of the study are to (1) develop improved tree growth models on Minnesota's Aspen-Birch and Northern Pine Inventory Units, (2) calibrate the model with FIA inventory data using physiographic class as a measure of site productivity and the average-adjusted model form, and (3) compare the model predictions with the recalibrated model (called STEMS-FIA).

BACKGROUND

Modeling Inventory Data

The North Central FIA unit uses a growth model-enhanced sampling design to inventory forests. To update previously measured plots, STEMS (Belcher *et al.* 1982), a distance-independent individual-tree growth model, was used to predict the growth of trees from the last inventory to the present. STEMS was calibrated from a variety of remeasured data sources—including research and industrial plots. Most were fixed-radius plots of 1/10 acre to 1/5 acre, representing small, fairly homogeneous areas. However, inventory plots often represent more diverse forest conditions than those used in the STEMS calibration. FIA survey plots were sampled using a variable-radius cluster sampling design covering a 1-acre sample area. Information from the cluster points is aggregated to represent the condition surrounding the center point. Complications arise when distinctly different forest conditions are represented by the aggregate stand condition. Variables derived from the tree lists, such as stand basal area, will misrepresent the local growing condition around each tree and hence have greater variability than those derived in the calibration of STEMS. However, since the new AFIS model is being developed from inventory data for an inventory application, a broader variable base is available than with the calibration of STEMS. The inclusion of these variables into the model may help account for more of the variability in growth estimates.

The traditional measure of site productivity used in growth models is site index. While measurement of site index is often imprecise and inaccurate (Bailey and Brooks 1994, McRoberts 1996, McRoberts *et al.* 1994), STEMS is sensitive to errors in site index (Gertner and

---

Mathematical Statistician, USDA Forest Service, North Central Research Station, 1992 Folwell Avenue, St. Paul, MN 55108, USA.

Dzialowy 1984). FIA inventories also record physiographic class (a measure of soil and water conditions that affect tree growth). Sites are classified into five classes from xeric to hydric, indicating their response to varying soil, climate, and topographic conditions. We have assumed that assignment to one of five classes is more precise than estimation of site index. This study will explore the substitution of physiographic class for site index as a measure of site productivity.

Model Form

There are two conceptual approaches to model development (Wykoff 1990) based on how we view the world—either in terms of potentials and different degrees of realization of those potentials or as averages and adjustments to those averages. The first approach, the "potential-modifier," (Belcher *et al.* 1982, Hahn and Leary 1979, Holdaway 1984, Shifley 1987) was used in the STEMS model. Models based on this approach have a potential component and a modifier component that are modeled sequentially. First, the potential diameter growth of competition-free trees is modeled, and second, a competitive adjustment is applied to reduce the potential growth to that actually observed. Modeling growth of competition-free trees is not intuitively clear (nor is it an observable feature of the stand), and various researchers have chosen differing approaches. Problems with this two-stage model form include the difficulties in representing an unobservable tree characteristic; the lack of direct statistical methods to reliably estimate the precision of growth predictions; and the difficulty of comprehending the underlying model structure or incorporating additional variables into the model.

The second model form, the "average-adjusted" (or composite) approach, is presented in this paper. This approach attempts to include the most relevant factors influencing growth in an average expression and to adjust growth based on its deviation from the average condition (Lemmon and Schumacher 1962, West 1980, Wykoff 1990). Advantages of the average-adjusted model form include: it fits an observable quantity, it provides for statistical measures of precision and significance tests for variable entry, the features of the model are easier to understand, and it easily accommodates the inclusion of additional FIA variables.

DATA

The inventory data (using a 10-point cluster sample) came from Minnesota's Aspen-Birch and Northern Pine Inventory Units. At each cluster subpoint, trees ≥ 5.0 inches dbh are sampled with a 37.5 BAF prism. Smaller trees (1.0-5.0 inches dbh) are selected on 1/300-acre fixed-area plots on all 10 subpoints (before 1986, fixed-area plots at only the first three points were measured). Four species were modeled—red pine (*Pinus resinosa* Ait.), balsam fir (*Abies balsamea* (L.) Mill.), quaking aspen (*Populus tremuloides* Michx.), and paper birch (*Betula papyrifera* Marsh.). Plot data initially recorded in the 1977 or 1990 inventories and remeasured in the first subsequent revisit were used. The database was restricted to undisturbed timberland plots with all trees having two diameter measurements. A systematic sample of every fourth plot was set aside for model validation, as described by Lessard (2000). Models were calibrated on the remainder of the plots.

METHODS

Model Fitting

The Weibull function was chosen because it is well suited to describing biological processes. It has been commonly used to represent the tree diameter distribution because of its flexibility (Bailey and Dell 1973). The model form simultaneously produces biologically reasonable and statistically accurate predictions. The usual expression of the three-parameter Weibull probability density function is:

$$f(X) = (C/B)\,((X-A)/B)^{C-1}\, e^{\left(-((X-A)/B)^{C}\right)}. \qquad [1]$$

If A=0, this reduces to a two-parameter Weibull function. When rescaled by a multiplier, it has the properties of a growth function and yields the modified three-parameter Weibull distribution function. In simplified expression, this equation forms the core diameter growth model used in this research:

$$E(GR) = b_1\, DBH^{(b_3-1)}\, e^{\left(-b_2\, DBH^{b_3}\right)} \qquad [2]$$

Other researchers have proposed related functions: $E(GR) = b_1$ DBH exp ($-b_2$ DBH) (Leary 1970) and $E(GR) = b_1$ DBH^{b_3} exp ($-b_2$ DBH) (Zeide 1993).

A linear combination of stand and tree exploratory variables were entered in the exponent in [2] to further adjust growth, yielding:

$$E(GR) = b_1\, DBH^{(b_3-1)}\, e^{\left(-b_2\, DBH^{b_3} + ADJ\right)} \qquad [3]$$

where *DBH* = average dbh over the interval, *GR* = average annual diameter growth, $ADJ = \sum b_i f_i(VAR_i)$, VAR_i = stand and tree variables, and the b_i's are regression parameters. The modified Weibull model, with additional terms in the exponent, is capable of incorporating the nonlinear effects of various predictor variables through transformations of the independent variables. Biologically constrained transformations were used to provide realistic growth effects. Various transformations were tested for each variable across species, and the one that tended to minimize sum of squares and provided logical biological behavior was selected. Transformations were standardized to yield a zero adjustment under "average" conditions. For ease, roughly average conditions across all species were used. The model has been geared to an inventory application—meaning that the maximum projection interval is assumed to be relatively short, and hence biological constraints on maximum stand basal area have not been modeled. This model form is general enough to be applied to all potential tree species and FIA predictor variables, thus forming the basis of a generalized tree-level modeling system.

Explanatory variables obtained from the FIA measured variables are diameter (DBH), crown ratio code (CR), crown class (CC), site index (SI), and physiographic class (PHY). Coding and definition of these variables is given in Hansen *et al.* (1992). Calculated or derived variables are plot basal area per acre (BA), number of trees per acre (NT), average stand diameter (AD), relative tree diameter (REL=DBH/AD), and basal area in trees larger than the subject tree (BAL). CC, NT, BAL, and PHY are variables not used in the original STEMS model.

Competition among trees within a stand affects individual tree growth. In distance-independent models, measures of overall crowding within a stand are represented by BA and NT, and measures of relative competitiveness of an individual tree to the neighboring trees are expressed by REL and BAL. CC also provides knowledge of competitive status.

Transformations of the predictor variables, together with interactions, were used to explore relationships between the independent variable set and diameter growth. Many interactions were tested and they predicted reasonable growth behavior. But while increasing the complexity of the model, they did not practically improve it. The Weibull model [3] was fit using nonlinear least squares; variables entered the equations only if significant at p=0.05. The final model selected is:

$$E(GR) = b_1 DBH^{(b_3-1)} e^{\left(-b_2 DBH^{b_3} + ADJ\right)} \qquad [4]$$

where

$$\begin{aligned} ADJ &= b_4 * (CR - 4) + \exp(b_5 * (BAL - 50)) - 1 \\ &+ b_6 * \log((DBH / AD) / 1.5) \\ &+ \exp(b_7 * (NT - 900.)) - 1 \\ &+ b_8 * (BA - 100) + b_9 * (AD - 5) \\ &+ b_{10} * (\exp(CC / 3) - 2.718) \\ &+ b_{11} * (PHY - 5) + b_{12} * (PHY - 5)^2. \end{aligned}$$

Note that DBH also enters the equation in the ADJ term through relative diameter, expressed as DBH/AD.

We can demonstrate graphically how the AFIS model in [4] behaves. When REL is expressed as DBH/AD, it produces a set of average diameter curves of diameter growth by diameter. Diameter increment increases to a maximum and then slowly decreases, approaching zero as the tree matures. Figure 1a shows how the AFIS model would grow red pine trees of a given DBH found growing in a young stand of AD = 4 inch for CR values of 2 (low), 5 (medium), and 8 (high). To account for the remaining variables, CC, BA, and NT in the model have been set to values concomitant with a 4-inch AD stand, and BAL has been expressed as a function of DBH. Figure 2a shows the same graph for a mature red pine stand of AD = 12 inch. The plots portray the range of DBH values typically found on a 4-inch and 12-inch AD stand, respectively.

Figures 1b and 2b show how the same conditions are modeled by STEMS-FIA. There are some obvious differences between the models used in AFIS and STEMS-FIA. The growth assigned a tree due to its relative position in the stand is handled differently by the two models. The STEMS-FIA model applies an ascending relative diameter influence with increasing DBH regardless of stand maturity. The AFIS model allows for the understory trees on a mature stand to demonstrate faster growth than the larger overstory trees, which are diminishing in growth. Scatterplots of the data indicate that this is reasonable growth behavior. CR is entered additively in STEMS and multiplicatively in AFIS. The differences in CR effect are more important on the edges of the CR and DBH range. For the largest trees (unaffected by competition), the models vary greatly in how they apply growth, due both to the CR effect and the underlying shape of the functions. The predicted diameter growth curve with the STEMS-FIA model is concave downward, whereas the AFIS model has an inflection point that provides for a slower approach to zero for the largest trees. Since there are very few trees in the inventory database above 25 inches, it is impossible to determine from the data which model is better.

Verification and Validation of Models

The AFIS model was tested by inserting model equations and parameters into a validation version of the STEMS tree growth projection system. The newly developed model was first verified against the calibration data, and the data were analyzed for trends in diameter residuals against predictor variables. If no significant trends were found, validation of the model was performed. Statistics evaluated included annualized mean errors, root mean square error (RMSE), model efficiency (as measured by relative improvement in RMSE) and r-square values. Model efficiency is defined as RMSE (STEMS-FIA) /

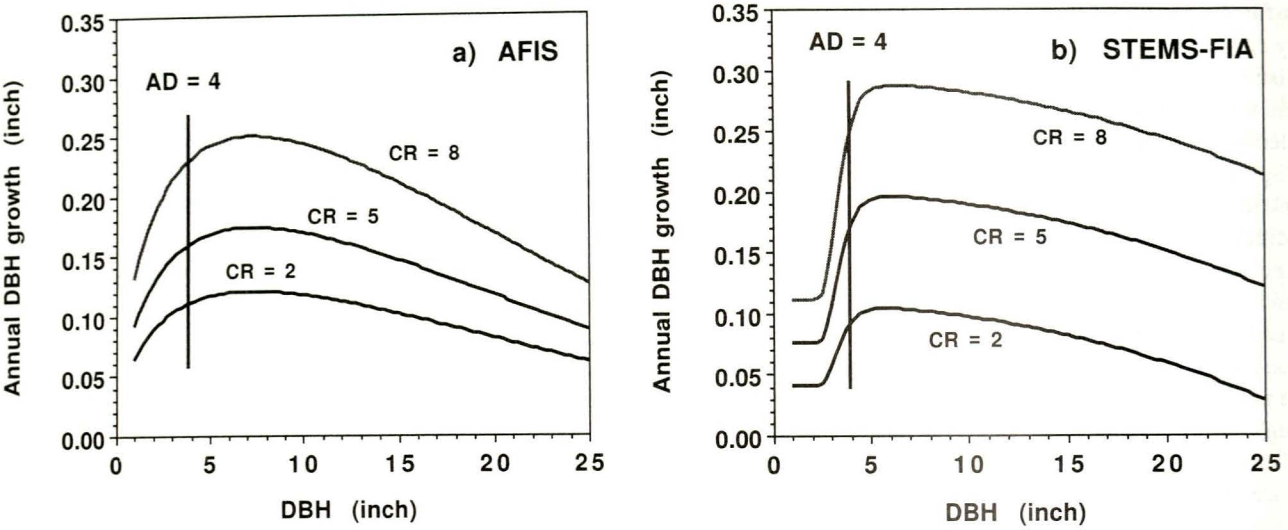


Figure 1.—*Diameter growth curves for red pine trees growing on a young stand (4-inch average diameter) as modeled by a) AFIS and b) STEMS-FIA. Low, moderate, and high crown ratio (CR) values are given.*

RMSE (AFIS). This provides a measure of the increase in precision (or decrease in residual variability) of the model over the STEMS-FIA model. Note that RMSE is a statistical measure that incorporates both bias and variability.

Accuracy and precision of the predictions were evaluated for tree diameter and stand basal area. The tree-level analysis evaluates the growth component of the model, whereas the stand-level analysis evaluates the combination of the growth and mortality components. Tree-level statistics were provided on all trees observed and predicted alive over the growth interval for the target species. Plot-level statistics were derived for plots of the corresponding cover types. The model verification and validation include a comparison of the AFIS model with the STEMS-FIA model (Lessard 2000). Both models used the STEMS mortality equations with localized mortality adjustments based on their modeled growth (Smith 1983). Since both AFIS and STEMS-FIA were calibrated on local data, neither used diameter adjustments to localize the model.

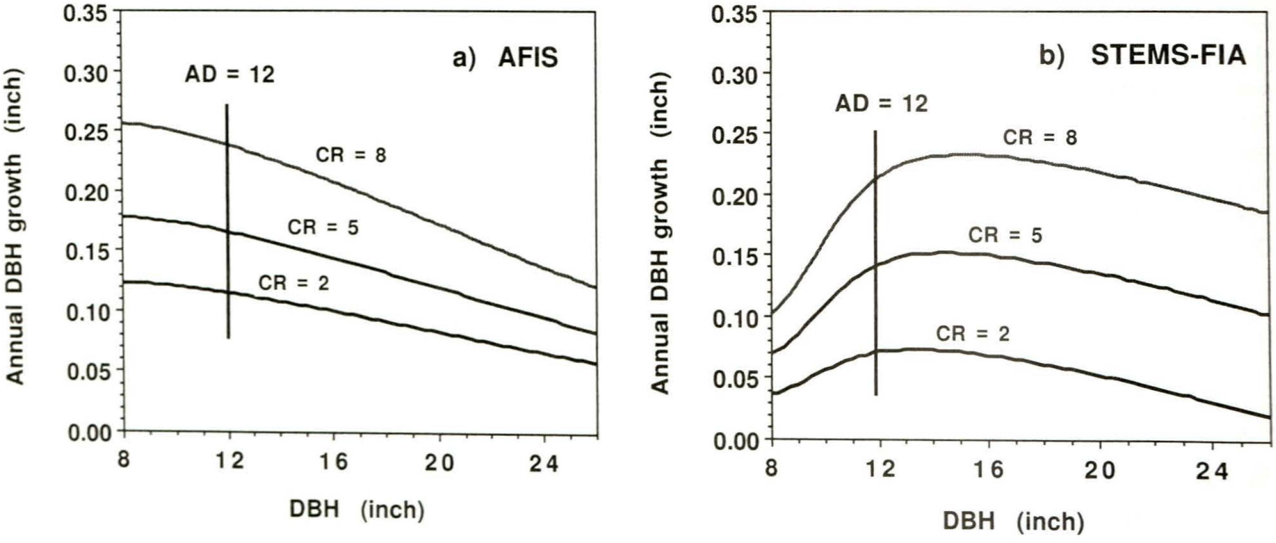


Figure 2.—*Diameter growth curves for red pine trees growing on a mature stand (12-inch average diameter) as modeled by a) AFIS and b) STEMS-FIA. Low, moderate, and high crown ratio (CR) values are given.*

Tests of Model Improvements

Tests were also made of the suitability of using (1) PHY in place of SI as a measure of site productivity and (2) the average-adjusted versus potential-modifier model form. First, site productivity measures were tested by replacing PHY with SI in the AFIS model form and re-estimating the parameters. SI was entered using the linear transformation: SI-60. When the appropriate SI was not recorded for the tree species, SI was set to 60, thus effectively dropping its influence from the equation. This model is called AFIS-SI. Second, the model form was tested by comparing the AFIS-SI model with STEMS-FIA (both use SI, but have a different model form).

RESULTS

Parameter values and transformations of the predictor variables for the AFIS model are given in table 1. Results of the model comparisons on the calibration and validation databases are given for the tree-level analysis (table 2) and the plot-level analysis (table 3). No obvious trends in residuals plotted against predictor variables for the AFIS model were found, except for some mild curvilinear trends and fluctuations in the largest trees (representing only a fraction of the trees).

Accuracy of the models, pertaining to both the calibration/validation databases, showed minimal differences between the STEMS-FIA and AFIS models for DBH predictions (tables 2, 4) and stand BA predictions (tables 3, 5). Improvement in precision of the models as measured by the model efficiency statistic (EFF) show that DBH predictions for the AFIS model were improved on all species on the calibration database and on three of four species on the validation database. At the stand level, BA predictions were improved on three of four species on both databases. For the AFIS model on the validation database, r^2 values ranged from .084 to .562 for annualized DBH growth predictions and .350 to .817 for annualized BA growth predictions. R^2 values for plot-level BA growth showed stronger correlations than for tree-level DBH growth. Since we are more concerned with the higher level attributes of the model, this is encouraging.

Across both data sets, the species most consistently improved in precision (for both DBH and BA predictions) was balsam fir. Quaking aspen was improved on DBH predictions, but not necessarily on BA predictions. Paper birch predictions were better for BA than DBH. Some of these differences may be due to problems in the mortality model included in the stand-level analysis.

Results of the tests of model improvements (a substitute measure of site productivity and the average-adjusted model from) are given in tables 4 (tree-level) and 5 (plot-level). Calibration and validation results have been

Table 1.—*Model parameter estimates for the AFIS model equation [4] for four species in the Aspen-Birch and Northern Pine Units of northern Minnesota*

	Estimates			
Parameters	**Red pine**	**Balsam fir**	**Quaking aspen**	**Paper birch**
b1	1.00000*	1.00000*	1.00000*	1.00000*
b2	0.34122	0.54916	0.38574	0.73029
b3	0.70717	0.60225	0.58417	0.35746
b4	0.11923	0.15509	0.11609	0.14361
b5	-0.00585	-0.00094	-0.00532	-0.00432
b6	1.08781	1.26480	1.11420	0.97978
b7	-0.00026	-0.00030	-0.00027	-0.00026
b8	0.00000*	0.00000*	0.00385	0.00252
b9	0.13040	0.21274	0.16785	0.15905
b10	-0.05979	-0.03575	-0.09480	-0.08142
b11	-0.04390	-0.09880	0.00000	0.00000
b12	0.00000	0.00000	-0.05926	-0.05805

* Parameter not significant at p = .05 and set to 1.0 or 0.0 as appropriate.

Table 2.—*The annualized diameter prediction errors for the STEMS-FIA and AFIS models on the calibration and validation databases*

Species	Model	Number of trees	Mean residual[1]	RMSE	EFF[2]	r-sq[3]	Change in r-sq
Calibration			*Inches*	*Inches*			
Red pine	STEMS-FIA	1,360	.000	.0689		.437	
Red pine	AFIS	1,360	-.001	.0673	1.02	.454	.017
Balsam fir	STEMS-FIA	5,909	.000	.0573		.304	
Balsam fir	AFIS	5,909	.001	.0546	1.05	.366	.062
Quaking aspen	STEMS-FIA	15,383	.002	.0717		.172	
Quaking aspen	AFIS	15,383	-.000	.0670	1.07	.217	.045
Paper birch	STEMS-FIA	5,461	-.001	.0486		.117	
Paper birch	AFIS	5,461	.001	.0477	1.02	.130	.013
Validation							
Red pine	STEMS-FIA	501	.013	.0731		.560	
Red pine	AFIS	501	.011	.0734	1.00	.562	.002
Balsam fir	STEMS-FIA	1,924	.001	.0599		.327	
Balsam fir	AFIS	1,924	.001	.0576	1.04	.383	.056
Quaking aspen	STEMS-FIA	5,348	.004	.0725		.157	
Quaking aspen	AFIS	5,348	-.001	.0680	1.07	.173	.016
Paper birch	STEMS-FIA	1,708	.003	.0666		.075	
Paper birch	AFIS	1,708	.004	.0657	1.01	.084	.009

[1] Positive residuals indicate an underprediction.

[2] Efficiency of the new model is calculated by EFF = RMSE (STEMS-FIA) / RMSE (AFIS).

[3] The r^2 (r-sq) is calculated as the square of the coefficient of correlation between predicted and observed annualized growth.

Table 3.—*The annualized stand basal area prediction errors are the STEMS-FIA and AFIS models on the calibration and validation databases (see footnotes of table 2)*

Cover type	Model	Number of plots	Mean residual	RMSE	EFF	r-sq	Change in r-sq
Calibration			*Sq ft/ac*	*Sq ft/ac*			
Red pine	STEMS-FIA	62	.219	2.055		.621	
Red pine	AFIS	62	-.320	1.992	1.03	.645	.024
Balsam fir	STEMS-FIA	228	.604	2.008		.370	
Balsam fir	AFIS	228	-.430	1.879	1.07	.437	.067
Quaking aspen	STEMS-FIA	1.296	.315	2.053		.471	
Quaking aspen	AFIS	1,296	-.352	2.135	.96	.466	-.005
Paper birch	STEMS-FIA	247	.467	1.820		.177	
Paper birch	AFIS	247	-.328	1.724	1.06	.187	.010
Validation							
Red pine	STEMS-FIA	25	-.515	1.694		.887	
Red pine	AFIS	25	.506	1.696	1.00	.817	-.070
Balsam fir	STEMS-FIA	62	.246	2.270		.288	
Balsam fir	AFIS	62	-.210	2.050	1.11	.421	.133
Quaking aspen	STEMS-FIA	443	.241	1.931		.424	
Quaking aspen	AFIS	443	-.265	1.815	1.06	.533	.109
Paper birch	STEMS-FIA	71	.534	1.949		.234	
Paper birch	AFIS	71	-.517	1.753	1.11	.350	.116

Table 4.—*The annualized diameter prediction errors for STEMS-FIA, AFIS-SI, and AFIS (with physiographic class in place of SI) models on the calibration and validation databases (see footnotes of table 2)*

Model	Number of trees	Mean residual	RMSE	EFF	r-sq	Change in r-sq
		Inches	*Inches*			
Calibration						
STEMS-FIA	28,113	.0011	648		.292	
AFIS-SI	28,113	-.0006	0615	1.05	.347	.048
AFIS	28,113	.0001	0612	1.06	.347	.055
Validation						
STEMS-FIA	9,481	.0034	0691	.266		
AFIS-SI	9,481	-.0020	.0659	1.05	.308	.042
AFIS	9,481	.0013	.0659	1.05	.308	.042

Table 5.—*The annualized stand basal area prediction errors for STEMS-FIA, AFIS-SI, and AFIS (with physiographic class in place of SI) models on the calibration and validation databases (see footnotes of table 2)*

Model	Number of plots	Mean residual	RMSE	EFF	r-sq	Change in r-sq
Calibration		*Sq ft/ac*	*Sq ft/ac*			
STEMS-FIA	1,833	-.331	1.976		.449	
AFIS-SI	1,833	-.320	2.039	.97	.458	.009
AFIS	1,833	-.358	2.049	.96	.456	.007
Validation						
STEMS-FIA	601	-.225	1.974		.437	
AFIS-SI	601	-.210	1.810	1.09	.543	.106
AFIS	601	-.257	1.829	1.08	.536	.099

averaged across all trees and hence are weighted in favor of quaking aspen (with 15,383 trees). PHY (the physiographic class), used as an indicator of site productivity, performed similarly to SI. The AFIS-SI model showed moderate improvement over the potential-modifier model (used in STEMS-FIA).

In summation, for all four species on the validation database, precision of DBH predictions improved by 5 percent and stand BA predictions by 8 percent for the AFIS model over the STEMS-FIA model.

CONCLUSIONS

The development and evaluation of a new model form, applied to four species on the Aspen-Birch and Northern Pine Inventory Units of Minnesota, was undertaken. The model, AFIS, was based on the modified three-parameter Weibull function. The model was fit in one step as a linear combination of transformed variables in the exponent reflecting departures from the average condition. The results indicate that the AFIS model performs moderately better than the STEMS-FIA model. The AFIS model design also has many desirable features: it uses a simple, flexible model form; allows for the complex relationships between variables to be expressed by simple biologically reasonable transformations; provides for inclusion of additional inventory variables (including climatic variables), significance testing of variable entry and precision estimates; and is easy to calibrate. However, for those who believe strongly in the biological concept of "potential" growth in plant dynamics and are less interested in precision and climatic questions, the potential-modified approach may be appropriate.

In the test of using physiographic class in place of site index, no difference was found. However, when the precision of site productivity measures is considered, physiographic class may well out-perform site index.

The AFIS model will be retained for further study in both the upcoming incorporation of a climatic component into the growth model and the precision analysis (McRoberts *et al.* 2000).

ACKNOWLEDGMENTS

The author thanks Ronald McRoberts for his assistance with this research. This project was financially supported by the Lakes States Alliance.

The following people reviewed this manuscript: Ronald McRoberts, Gary Brand, and Veronica Lessard, USDA Forest Service, North Central Research Station, St. Paul, MN, USA; and Rolfe Leary, USDA Forest Service (Retired).

LITERATURE CITED

Bailey, R.L.; Brooks, J.R. 1994. Determining site index and estimating timber volumes without measuring heights. Southern Journal of Applied Forestry. 18: 15-18.

Bailey, R.L.; Dell, T.R. 1973. Quantifying diameter distributions with the Weibull function. Forest Science. 19: 97-104.

Belcher, D.M.; Holdaway, M.R.; Brand, G.J. 1982. STEMS—the Stand and Tree Evaluation and Modeling System. Gen. Tech. Rep. NC-79. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 18 p.

Gertner, G.Z.; Dzialowy, P.J. 1984. Effects of measurement errors on an individual tree-based growth projection system. Canadian Journal of Forest Research. 14: 311-316.

Hahn, Jerold T.; Leary, Rolfe A. 1979. Potential diameter growth functions. In: A generalized forest growth projection system applied to the Lake States region. Gen. Tech. Rep. NC-49. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 22-26.

Hansen, M.H.; Frieswyk, T; Glover, J.F.; Kelly, J.F. 1992. The Eastwide forest inventory data base: users manual. Gen. Tech., Rep. NC-151. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 48 p.

Holdaway, Margaret R. 1984. Modeling the effect of competition on tree diameter growth as applied in STEMS. Gen. Tech., Rep. NC-94. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 9 p.

Leary, R. 1970. System identification principles in studies of forest dynamics. Res. Pap. NC-45. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 35 p.

Lemmon, P.E.; Schumacher, F.X. 1962. Volume and diameter growth of ponderosa pine trees as influenced by site index, density, age, and size. Forest Science. 8: 236-249.

Lessard, Veronica. 2000. Calibration of the STEMS diameter growth model on FIA data. In: Hansen, M., Burk, T., eds. Integrated tools for natural resources inventories in the 21st century. Proceedings of the IUFRO conference; 1998 August 16-20; Boise, ID. Gen. Tech. Rep. NC-212. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 501-508.

McRoberts, Ronald E. 1996. Estimating variation in field crew estimates of site index. Canadian Journal of Forest Research. 26: 560-565.

McRoberts, R.E.; Holdaway, M.R.; Lessard, V.C. 2000. Comparing the STEMS and AFIS growth models with respect to the uncertainty of predictions. In: Hansen, M., Burk, T., eds. Integrated tools for natural resources inventories in the 21st century. Proceedings of the IUFRO conference; 1998 August 16-20; Boise, ID. Gen. Tech. Rep. NC-212. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 539-548.

McRoberts, R.E.; Hahn, J.T.; Hefty, G.J.; Van Cleve, J.R. 1994. Variation in forest inventory field measurements. Canadian Journal of Forest Research. 24: 1766-1770.

Shifley, S.R. 1987. A generalized system of models forecasting central states tree growth. Res. Pap. NC-279. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 10 p.

Smith, W.B. 1983. Adjusting the STEMS regional forest growth model to improve local predictions. Res. Note NC-297. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experimental Station. 5 p.

West, P.W. 1980. Use of diameter increment and basal area increment in tree growth studies. Canadian Journal of Forest Research. 10(1): 71-77.

Wykoff, W.R. 1990. A basal area increment model for individual conifers in the Northern Rocky Mountains. Forest Science. 36: 1007-1104.

Zeide, Boris. 1993. Analysis of growth equations. Forest Science. 39(3): 594-616.

Validation Databases for Simulation Models: Aboveground Biomass and Net Primary Productivity (NPP) Estimation Using Eastwide FIA Data

Jennifer C. Jenkins and Richard A. Birdsey

Abstract.—As interest grows in the role of forest growth in the carbon cycle, and as simulation models are applied to predict future forest productivity at large spatial scales, the need for reliable and field-based data for evaluation of model estimates is clear. We created estimates of potential forest biomass and annual aboveground production for the Chesapeake Bay watershed region from USDA Forest Service Forest Inventory and Analysis data. These estimates were developed primarily for model evaluation and represent the pilot phase of an effort to estimate potential and actual forest biomass and annual production for the entire nation.

As interest in the impacts of climate change and enhanced CO_2 on ecosystem processes has grown, process model predictions of vegetation growth rates and biomass accumulation are being developed at an accelerating rate. Even when they are based on the same input data sets, however, estimates made by different models can differ from one another by as much as 100 percent (VEMAP Members 1995, Jenkins *et al.* 1998). Still, scientists cannot be sure whether their models are giving accurate predictions, even for current conditions, because the availability of field-collected validation data has not kept pace with the need for model predictions. The objective of this study was to develop methods for estimating aboveground forest net primary productivity (ANPP) and aboveground biomass from USDA Forest Service Forest Inventory and Analysis (FIA) data using methods that would ensure compatibility with the model-based estimates. Assuming that the extensive network of field-measured FIA plots represents the best available estimate of current conditions, the potential ANPP and biomass predictions created from this work can be compared with process model predictions to evaluate the accuracy of the models.

The Chesapeake Bay, the nation's largest estuary, has experienced several anthropogenically induced stresses during the 19th and 20th centuries that have resulted in altered nutrient, sediment, and hydrologic regimes. Nitrogen (N) loss from forested systems has been cited as an important contributor to the nutrient loadings into the Bay. Since C and N cycles are inextricably linked in forested systems, assessing actual and potential C fixation rates in the Chesapeake Bay watershed is important for those attempting to understand the flow of N through the watershed's forests. Further, evaluating the accuracy of model predictions for this region will enable policymakers to rely with confidence on those predictions.

METHODS

Study Area

Estimates are presented for the seven-state mid-Atlantic (USA) region that surrounds the Chesapeake Bay watershed. For simplicity of analysis and to maximize sample size and geographical coverage, the states of Virginia, West Virginia, Maryland, Delaware, New Jersey, Pennsylvania, and New York were treated in their entirety.

Data Source

Data were obtained from the Eastwide Forest Inventory Data Base (Hansen *et al.* 1992) established and maintained by USDA Forest Service Forest Inventory and Analysis (FIA) units in the Northeastern, North Central, Southern, and Southeastern Research Stations. The plots in the seven-state region treated here represent a subset of the FIA plots in the region.

Choosing Plots for Analysis

Most forest ecosystem process models are designed to predict C, N, and/or water cycling rates in undisturbed, mature forests. To provide the most accurate model validation, we restricted the sample of FIA plots used for this study (cf. McNulty *et al.* (1994)) to those that most closely represented modeled conditions. In particular, all plots meeting the following conditions were included in the sample: (a) remeasured at least once; (b) classified as timberland or reserved timberland for the two most recent remeasurement periods; (c) classified as either poletimber or sawtimber in size at the time of the most recent measurement inventory; d) no evidence of damage by

---

Research Forester and Program Manager, respectively, USDA Forest Service Northern Global Change Program, Radnor, PA, USA.

insects, logging, disease, or fire between the two most recent inventories; and (e) "natural" in origin (i.e., not planted). Using these guidelines, we found 3,757 plots meeting all five criteria, out of 23,322 total plots in the seven-state region.

Because these estimates are based on a subset of the plots meant to represent the maximum biomass accumulation and ANPP conditions that are typically predicted by simulation models, we designate the predictions developed and presented here as "potential." There are weaknesses with this definition: in particular, we have not performed analyses to confirm that they do represent maximum achievable biomass accumulation and growth rates, and the use of stand size to represent closed-canopy mature conditions may be less appropriate than a variable such as basal area or stocking. However, the "potential" designation will serve to set these predictions apart from the "actual" conditions based on the full sample of inventory plots.

Aboveground Biomass

Individual FIA units develop and publish estimates of growing-stock volume and tree biomass (usually on a green-weight basis) to accompany the inventory statistics for each inventory period. The units also develop estimates of timber growth during the inventory cycle. However, those estimates typically use the entire inventory sample to obtain estimates of actual biomass and forest growth. Because of our emphasis on "potential" growth for simulation model validation, we developed separate estimates of aboveground biomass for the subsample of plots described above.

Estimates of aboveground forest biomass (dry-weight basis) were created for each plot by adding together the biomass contributions from each of the trees (both live and dead, expressed per unit area) on that plot. Regression equations were used to predict aboveground tree biomass on a dry-weight basis from diameter at breast height (dbh). The approach used by Wharton *et al.* (1997), in which biomass equations from different regions were used to predict biomass of individual species, was adopted for this study. Although most biomass equations are developed locally, independent studies (Jacobs and Monteith 1981, Barrett and Jastrembski 1990) have suggested that the differences among tree biomass in different parts of a region may not be large enough to prevent the use of regional regression equations. For both this study and the Wharton *et al.* (1997) study, equations from Maine (Young *et al.* 1980) were used for all evergreen species in addition to red maple, yellow birch, and quaking aspen; equations from West Virginia (Wiant *et al.* 1977) were used for Appalachian deciduous species such as hickory, yellow-poplar, black cherry, and oak species; and equations from New York (Monteith 1979) were used for sugar maple, American beech, and white ash (table 1). Species for which regression equations did not exist were matched with species for which equations were available by comparing wood densities, as described in Appendix B of Wharton *et al.* (1997). We assumed that the equations typically used for live trees were appropriate for dead trees as well.

Aboveground Net Primary Productivity (ANPP)

Net primary productivity (NPP) is defined as the net production of organic matter per unit area per year. While total NPP includes both aboveground and belowground components, aboveground NPP (ANPP) is more commonly (and more easily) measured. Annual ANPP was found as:

$$\text{ANPP (kg ha}^{-1}\text{ yr}^{-1}) = \text{Wood production (kg ha}^{-1}\text{ yr}^{-1}) + \text{average annual litterfall (kg ha}^{-1}\text{ yr}^{-1}). \qquad (1)$$

Litterfall was not measured on these plots, so we used estimates developed by E. Matthews, W. Post, E.A. Holland and J. Sulzman (and cited in Brown and Schroeder (1998)) based on a review of the available literature for United States forests. Annual litterfall was estimated to be 3.2 Mg ha^{-1} yr^{-1} in spruce-fir forests, 4.0 Mg ha^{-1} yr^{-1} in pine forests, and 4.5 Mg ha^{-1} yr^{-1} in hardwood forests. We found annual wood production per tree as:

$$\text{Wood production per tree (kg yr}^{-1}) = [\text{aboveground biomass (kg) } (t_1) - \text{aboveground biomass (kg) } (t_0)]/[t_1 - t_0 \text{ (yr)}]. \qquad (2)$$

Biomass estimates for current conditions (t_1) were found on a tree-by-tree basis using species-specific regression equations as described above. To find biomass and biomass increment on a per hectare basis from tree-level measurements, the tree-level estimates were multiplied by an expansion factor representing the number of trees per unit area represented by that individual stem. Biomass estimates for each stem at the previous inventory (t_0) were found as described below.

Dbh measurements existed for two consecutive measurement periods for 89,938 live stems (all greater than 12.7 cm dbh). Average yearly diameter increment for these stems (for the period roughly from 1980 to 1990, depending on the state) was 0.3351 cm yr^{-1}. There were 12,082 dead stems in the current inventory, and 65,131 more were ongrowth stems (i.e., they were measured in the current inventory, but were too small—less than 12.7 cm dbh—to have been measured in the previous inventory (Birdsey and Schreuder 1992)).

Table 1.—*Aboveground tree-weight regression coefficients for selected species. From Wharton* et al. *(1997)*

Equation forms:

$$\ln Y = b_0 + b_1 \ln(D) \quad (1)$$

$$\log_{10} Y = \mathrm{LOG}_{10} b_0 + b_1 \mathrm{LOG}_{10}(D) \quad (2)$$

$$Y = b_0 + b_1(D) + b_2(D^2) \quad (3)$$

Y = dry weight (pounds (eqs. 1 and 2) or kg (eq. 3))
D = dbh (inches (eqs. 1 and 2) or millimeters (eq. 3))

Species	Coefficients b_0	b_1	b_2	Equation number
Balsam fir	0.5958	2.4017		1
Eastern white pine	0.4080	2.4490		1
Red pine	0.7157	2.3865		1
Spruce spp.	0.8079	2.3316		1
Hemlock	0.6803	2.3617		1
N. white-cedar	1.1182	1.9269		1
Larch	0.8162	2.2453		1
Red maple	0.9392	2.3804		1
Sugar maple	5.2480	0.3661	0.0076	3
Yellow birch	1.1297	2.3376		1
Hickory	1.9338	2.6209		2
American beech	5.3373	-0.3257	0.0072	3
White ash	3.2031	-0.2337	0.0061	3
Yellow-poplar	1.5779	2.5153		2
Black cherry	2.5883	2.4253		2
Aspen	0.4689	2.6087		1
White oak	1.2892	2.7010		2
Scarlet oak	2.6574	2.4395		2
Chestnut oak	2.1202	2.5344		2
Northern red oak	1.6891	2.6598		2
Black oak	2.1457	2.5050		2

For dead and ongrowth stems, we assumed that all trees (regardless of size) grew at the average rate for the region, and that dead stems had died halfway through the previous inventory. The diameter of dead trees at t_0 was found as:

$$\text{DBH (cm) at } t_0 = \text{DBH (cm) at } t_1 - [(0.3351 \text{ cm yr}^{-1})*(\text{remeasurement period length (yr)}/2)]. \quad (3)$$

Ongrowth trees were grown back to their previous diameter using a similar equation:

$$\text{DBH (cm) at } t_0 = \text{DBH (cm) at } t_1 - [(0.3351 \text{ cm yr}^{-1})*(\text{remeasurement period length (yr)})]. \quad (4)$$

If the above equations resulted in a negative diameter, DBH (and thus biomass) at t_0 were set to zero.

These estimates do not include measures of seedling and shrub production. Based on the work of Wharton *et al.* (1997) in New York, it is likely that this exclusion has biased our results downward by less than 3 percent.

Stand Characteristics

Plot basal area (m^2 ha^{-1}) (BA) was found by adding together the BA contributions from each of the live trees greater than 2.54 cm dbh on each plot. BA values ranged from 1.36 to 61.28 m^2 ha^{-1}, with a mean of 24.09 m^2 ha^{-1}. The sum of tree circumferences was used as a surrogate for sapwood area (cf. Smith (1986)) and was found by adding together the contribution of each live tree to a per hectare estimate of circumference outside bark (cm ha^{-1}). For all other stand characteristics (stocking, stand size, forest-type group, and stand age), the plot-level data from the Eastwide Data Base (Hansen *et al.* 1992) were used.

Ecoregions and Climate Data

The study region spans seven of the ecological Provinces delineated by the ECOMAP team of the USDA Forest Service (McNab and Avers 1994) and 79 of the smaller Sections described for the eastern United States by Keys *et al.* (1995). Province boundaries were obtained from the data published on CD-ROM by Keys *et al.* (1995). Plots were identified with individual Provinces by overlaying the plot locations with a map of Province boundaries (fig. 1). Because the approximate plot locations from the Eastwide Data Base are accurate to only within (roughly) 1 km, and because the Province boundaries are themselves fairly approximate, the error associated with this operation was considered small enough to ignore.

Temperature, precipitation, and elevation data were obtained by overlaying exact plot locations with maps representing average annual temperature (C), total annual precipitation (cm), and elevation above sea level (m). The climate maps were developed at 1-km resolution using modeling approaches as described by Pan *et al.* (1998), and the digital elevation model (DEM) was obtained from the United States Geological Survey at 1-km resolution. Across the study area, average annual temperature ranged from 4.21 to 15.38C, with an average of 9.28C. Total annual precipitation ranged from 77 to 173 cm yr^{-1} and averaged 110.56 cm yr^{-1}. Elevation ranged from 0 to 1,377 m above sea level, averaging 390 m for the region.

RESULTS

Aboveground Biomass

Results by Forest-Type Group, State, and Ecological Unit

Summarized by forest-type group, estimates of average aboveground biomass ranged from 107 Mg ha^{-1} in the loblolly-shortleaf pine forest-type group to 211.7 Mg ha^{-1} in the maple-beech-birch type group (table 2). Averaging results by state, the lowest average aboveground biomass (120.9 Mg ha^{-1}) was found in New Jersey and the highest (192.8 Mg ha^{-1}) was found in New York (table 3). When the results were summarized by ecological province, the lowest overall biomass in the region (133.0 Mg ha^{-1}) was found in the Southeastern Mixed Forest Province, while the highest (209.7 Mg ha^{-1}) was in the Adirondack-New England Mixed Forest-Coniferous Forest-Alpine Meadow Province (table 4). The range in biomass predictions was greatest when predictions were aggregated by forest-type group, and smallest when predictions were aggregated by state.

Multiplying the average potential aboveground biomass on timberland (Mg ha^{-1}) for each state by the total land area covered by timberland in that state, we estimate that the total potential aboveground biomass on timberland for the seven-state mid-Atlantic region is approximately 4.54 Pg (1 Pg = 10^{15} g). Taking 0.475 to represent the proportion of that biomass in carbon (Raich *et al.* 1991), the total potential C in aboveground standing biomass on timberland in the region is roughly 2.16 Pg. In contrast, Birdsey (1992) reported that a total of 1.57 Pg C can be found aboveground on timberland in this study region. The difference of roughly 30 percent between the two estimates might be seen as the difference between "actual" and "potential" aboveground C in standing biomass. Also based on data from Birdsey (1992), the C stored on timberland in this seven-state region makes up roughly 20 percent of the total aboveground C in all forested systems of the United States.

Trends in Aboveground Biomass

Not surprisingly, the best predictor of aboveground biomass at the plot level was basal area of live trees, as described by the equation:

$$\text{Log}_{10}\text{biomass (kg ha}^{-1}) = 14.07(\log_{10}(\text{basal area (m}^2\,\text{ha}^{-1}))) + 1.005 \qquad (5)$$

($n = 3{,}757$ plots; $R^2 = 0.593$, and p-values on coefficient and constant < 0.000).

In addition to basal area, aboveground biomass was also correlated with stocking, stand size classification (as sawtimber or poletimber), and forest-type group as described for each plot in the Eastwide Data Base. However, aboveground biomass as calculated here was not correlated with strongly climatic or physiographic characteristics such as temperature, precipitation, elevation, physiographic class, or site class (the latter two variables are described for each plot in the Eastwide Data Base as defined by Hansen *et al.* (1992)).

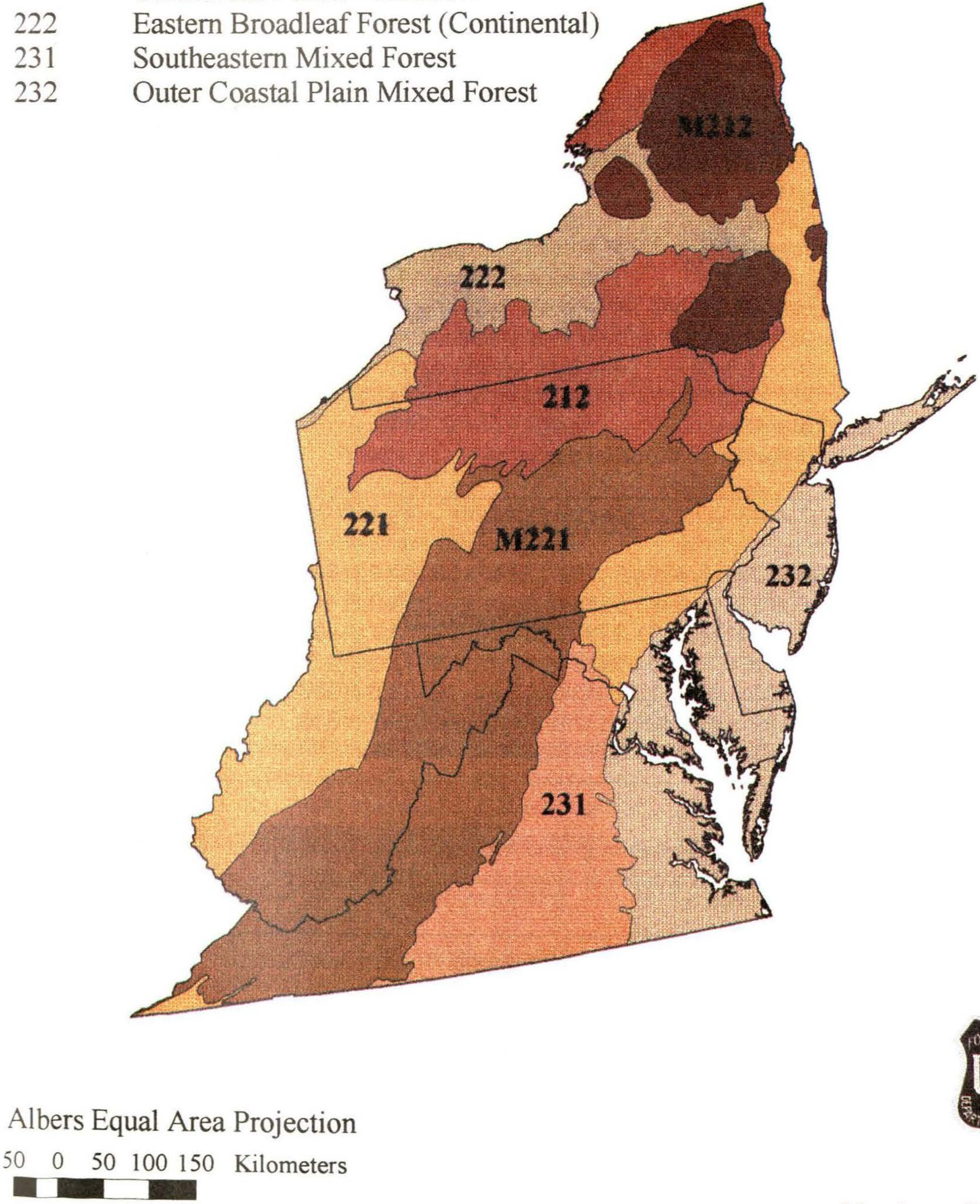
Wood Production and Aboveground Net Primary Productivity

Results by Forest-type Group, State, and Ecological Unit

Averaged by forest-type group, the lowest annual wood production (4,346.4 kg ha^{-1} yr^{-1}) occurred in the loblolly-shortleaf pine forest type (table 2). The range in annual wood production estimates (1,000 kg ha^{-1} yr^{-1}) between the least and most productive forest types was much narrower than the corresponding range in average aboveground biomass estimates (104.7 Mg ha^{-1}, or 104,700 kg ha^{-1}). The highest average annual wood production (5,227 kg ha^{-1} yr^{-1}) occurred in the aspen-birch type group. Because forest-type group was used to find annual litter production, these trends were identical for ANPP and for wood production.

KEY:

212	Laurentian Mixed Forest
M212	Adirondack - New England Mixed Forest Coniferous Forest - Alpine Meadow
221	Eastern Broadleaf Forest (Oceanic)
M221	Central Appalachian Broadleaf Forest - Coniferous Forest - Meadow
222	Eastern Broadleaf Forest (Continental)
231	Southeastern Mixed Forest
232	Outer Coastal Plain Mixed Forest


M212
222
212
221
M221
232
231
Albers Equal Area Projection
50 0 50 100 150 Kilometers

USDA Forest Service
Northern Global Change Program

Figure 1.—*Ecological Province boundaries for the mid-Atlantic (USA) region, as defined in digital data of Keys* et al. *(1995).*

Table 2.—*Summary of aboveground biomass, wood production, and aboveground NPP estimates by forest type group. All values are presented as mean (S.D.). Values within a column followed by different letters are significantly different, as determined by ANOVA ($p < 0.05$).*

Forest-type group description	**Plots**	**Aboveground biomass**	**Wood production**	**ANPP**
	Number	*Mg ha^{-1}*	*kg ha^{-1} yr^{-1}*	*kg ha^{-1} yr^{-1}*
Oak-Hickory	1,649	176.4 (63.6)^{d}	4815.8 (1513.8)^{bcd}	9315.8 (1513.8)^{c}
Maple-Beech-Birch	1,233	211.7 (87.6)^{e}	5042.3 (1450.3)^{d}	9542.3 (1450.3)^{d}
White-Red-Jack Pine	243	162.7 (69.3)^{bcd}	5037.6 (1565.6)^{cd}	9037.6 (1565.6)^{c}
Loblolly-Shortleaf Pine	183	107.0 (40.0)^{a}	4346.4 (2036.3)^{a}	8346.4 (2036.3)^{ab}
Oak-Pine	176	137.9 (53.0)^{bc}	4604.6 (1609.7)^{abc}	9104.6 (1609.7)^{c}
Elm-Ash-Cottonwood	121	141.4 (69.7)^{bc}	4395.5 (2027.5)^{ab}	8895.5 (2027.5)^{bc}
Aspen-Birch	67	137.4 (70.7)^{abc}	5227.0 (1844.4)^{d}	9727.0 (1844.4)^{d}
Spruce-Fir	51	131.9 (48.6)^{ab}	4761.4 (1548.5)^{abcd}	7961.4 (1548.5)^{a}
Oak-Gum-Cypress	33	169.0 (89.7)^{bcd}	4972.0 (2324.9)^{bcd}	9472.0 (2324.9)^{cd}
Longleaf-Slash Pine	1	200.0	4762.6	8762.6

Table 3.—*Summary of aboveground biomass, wood production, and aboveground NPP estimates by state. All values are presented as mean (S.D.). Values within a column followed by different letters are significantly different, as determined by ANOVA ($p < 0.05$).*

State	**Plots**	**Aboveground biomass**	**Total C in timberland**	**Wood production**	**ANPP**	**Annual total C storage in timberland**
	Number	*Mg ha^{-1}*	*Tg C = 10^{12} g C*	*kg ha^{-1} yr^{-1}*	*kg ha^{-1} yr^{-1}*	*Tg C yr^{-1} = 10^{12} g C yr^{-1}*
New York	1,258	192.8 (86.4)^{c}	587.72	4914.2 (1528.1)^{bc}	9302.8 (1548.7)^{cd}	14.98
Pennsylvania	1,086	188.3 (73.2)^{c}	609.26	5091.5 (1426.7)^{c}	9558.0 (1443.3)^{d}	16.47
West Virginia	704	180.0 (68.7)^{c}	415.54	4791.3 (1523.5)^{b}	9264.7 (1537.7)^{bcd}	11.06
Virginia	364	133.3 (52.6)^{a}	409.63	4654.5 (1944.9)^{b}	9017.2 (1919.5)^{b}	14.30
Maryland	211	159.5 (60.7)^{b}	79.03	4715.3 (1573.1)^{b}	9139.5 (1607.6)^{bc}	2.34
New Jersey	93	120.9 (72.3)^{a}	43.92	3324.6 (1710.9)^{a}	7668.7 (1818.7)^{a}	1.21
Delaware	41	168.2 (52.7)^{bc}	12.27	4860.6 (1464.6)^{bc}	9263.1 (1500.6)^{bcd}	0.35

Table 4.—*Summary of aboveground biomass, wood production, and aboveground NPP estimates by ecoregion (province). All values are presented as mean (S.D.). Values within a column followed by different letters are significantly different, as determined by ANOVA ($p < 0.05$).*

Province ID (USDA classification)	**Province description**	**Plots^{1}**	**Aboveground biomass**	**Wood production**	**ANPP**
		Number	*Mg ha^{-1}*	*kg ha^{-1} yr^{-1}*	*kg ha^{-1} yr^{-1}*
M221	Central Appalachian Broadleaf Forest - Coniferous Forest - Meadow	1017	173.5 (67.8)^{b}	4706.7 (1576.3)^{ab}	9169.6 (1596.9)^{ac}
212	Laurentian Mixed Forest	867	198.8 (79.5)^{d}	4983.2 (1402.7)^{c}	9422.6 (1416.7)^{c}
221	Eastern Broadleaf Forest (Oceanic)	744	175.8 (69.7)^{bc}	4900.0 (1504.8)^{bc}	9360.5 (1511.1)^{bc}
M212	Adirondack - New England Mixed Forest Coniferous Forest - Alpine Meadow	436	209.7 (90.3)^{d}	4926.2 (1321.3)^{bc}	9257.2 (1379.0)^{abc}
232	Outer Coastal Plain Mixed Forest	294	136.0 (60.5)^{a}	4556.7 (1896.2)^{a}	8908.7 (1941.3)^{a}
222	Eastern Broadleaf Forest (Continental)	226	175.8 (91.4)^{bc}	5163.4 (1977.1)^{c}	9590.4 (1987.1)^{c}
231	Southeastern Mixed Forest	160	133.0 (52.0)^{a}	5096.0 (1936.5)^{c}	9442.9 (1925.6)^{c}

[1] Due to the inexact nature of the boundaries, some of the FIA plots fell within areas classified as "water" on the ecoregion map; those plots were omitted from this analysis.

State boundaries provide convenient and understandable geographic units for analysis. Summarizing results by state, we found that New Jersey had dramatically lower wood production (3,324.6 kg ha^{-1} yr^{-1}) than any of the other states, perhaps because of its predominantly sandy soils. Virginia had the next lowest annual wood production, at 4,654.5 kg ha^{-1} yr^{-1} (table 2). Pennsylvania's timberland produced the highest average woody biomass increment, at 5,091.5 kg ha^{-1} yr^{-1}. The range in aboveground wood production was 1,767 kg ha^{-1} yr^{-1}. The corresponding range in ANPP was similar, at 1,889 kg ha^{-1} yr^{-1}.

When results were aggregated by ecological province, timberland plots falling within the Continental Eastern Broadleaf and Southeastern Mixed Forest Provinces had average annual wood production higher than that reported for any of the states or forest types (5,163.4 kg ha^{-1} yr^{-1} and 5,096.0 kg ha^{-1} yr^{-1}, respectively) (table 3). The lowest wood production (4,556.7 kg ha^{-1} yr^{-1}) was found for those plots falling within the Outer Coastal Plain Mixed Forest. Trends were similar for ANPP, with the Continental Eastern Broadleaf Forest having the highest ANPP (9,590.4 kg ha^{-1} yr^{-1}) and the Outer Coastal Plain Mixed Forest having the lowest ANPP (8,908.7 kg ha^{-1} yr^{-1}).

Multiplying the average potential wood production on timberland (kg ha^{-1} yr^{-1}) in each state by the amount of timberland in that state, we estimate that maximum aboveground biomass accumulation by forests on timberland in the mid-Atlantic region is about 127.82 Tg OM yr^{-1} (1 Tg = 10^{12} g). Again taking 0.475 as the proportion of carbon in biomass, mid-Atlantic forests may potentially sequester 60.71 Tg C yr^{-1} in aboveground biomass. It is important to note, again, that these figures do not represent the full sample of the inventory plots, and that they also do not include the C potentially being added to (or lost from) belowground biomass and soil organic matter.

Trends in Aboveground Wood Production and ANPP

The best individual predictor of aboveground wood production was plot-level basal area, as described by the equation:

$$\text{Log}_{10}\text{wood production (kg ha}^{-1}\text{ yr}^{-1}) = 1.345(\log_{10}(\text{basal area (m}^2\text{ha}^{-1}))) + 0.7957 \tag{6}$$

(n = 3,757 plots; $R^2 = 0.336$, and p-values on coefficient and constant < 0.000).

Adding stem density to the predictive equation explained ~10 percent more of the variation in wood production:

$$\text{Log}_{10}\text{wood production (kg ha}^{-1}\text{ yr}^{-1}) = 1.343(\log_{10}(\text{basal area (m}^2\text{ha}^{-1}))) + 0.131(\log_{10}(\text{stem density (stems ha}^{-1}))) + 0.6719 \tag{7}$$

(n = 3,757 plots; $R^2 = 0.435$, and p-values on coefficients and constant < 0.000).

Despite the assumed relationship between sapwood area, the sum of tree circumferences, and wood production, the sum of circumferences was a poorer predictor of wood production than was basal area:

$$\text{Log}_{10}\text{wood production (kg ha}^{-1}\text{ yr}^{-1}) = 0.111(\log_{10}(\text{sum of circumferences (cm ha}^{-1}))) + 0.5 \tag{8}$$

(n = 3757 plots; $R^2 = 0.289$, and p-values on coefficient and constant < 0.000).

Finally, aboveground biomass was a better predictor of wood production than the sum of tree circumferences, but a poorer predictor than basal area:

$$\text{Log}_{10}\text{wood production (kg ha}^{-1}\text{ yr}^{-1}) = 0.0178(\log_{10}(\text{aboveground biomass (kg ha}^{-1}))) + 0.7986 \tag{9}$$

(n = 3,757 plots; $R^2 = 0.310$, and p-values on coefficient and constant < 0.000).

These variables were also the strongest predictors of ANPP, but the predictive relationships were not as strong: basal area, stem density, and aboveground biomass explained between 2 and 5 percent less of the variation in ANPP than in wood production.

Other stand-level variables, such as stand size, forest-type group, and stand age were not strongly related to aboveground wood production or ANPP. Physical variables such as physiographic class, site class, precipitation, temperature, and elevation were not related at all to annual production, suggesting that inherent stand characteristics (and not these climatic or physiographic variables) may be the best predictors of annual forest growth rates in this region.

DISCUSSION

Current and Future C Assimilation

The patterns and magnitudes of woody biomass increments presented here are consistent with those presented by Brown and Schroeder (1998), who used data from the

Eastwide FIA Data Base to map biomass increments at the county level for the eastern United States. Based on the current analysis, aboveground C sequestration by live timberland in the region is currently potentially responsible for mitigating about 5 percent of the estimated annual emissions from fossil fuel and cement production in the United States (1.3 Pg yr^{-1}) (Marland *et al.* 1994). The magnitude of C accumulation in "dead" material (soil and forest floor) has historically been at least as great as that in aboveground live biomass (Birdsey and Heath 1995). Based on an analysis of FIA data collected over the past few decades, Birdsey and Heath (1995) concluded that United States forests (mostly in the eastern half of the nation) have actually been responsible for mitigating about 25 percent of annual the nation's C emissions.

In the very long term (200-300+ years), however, it is unlikely that eastern forests will continue to accumulate organic matter and C in their tissues, because substantial evidence suggests that NPP declines significantly with stand age (Gower *et al.* 1996, Ryan *et al.* 1997, Ryan and Yoder 1997). The average age for the plots analyzed here was 48.8 (+/- 23.4) years; decades are likely to pass before the growth rates for these forests reach a minimum.

What Determines Wood Production and Biomass Accumulation?

Physiographic characteristics such as drainage class, site index, and elevation were poor predictors of annual wood production. Similarly, climatic variables such as temperature and precipitation were not related to wood production or total aboveground biomass. Instead, measures of forest structure—basal area, stem density, stocking, forest composition, and the sum of tree circumferences—were the best predictors of annual production and total aboveground biomass. Yet the plots chosen for analysis in this study should most closely reflect differences in physiographic, edaphic, and climatic characteristics, because this sample was restricted to plots that had experienced no damage or harvesting since the last inventory and that should have represented closed-canopy forests.

Several explanations for this phenomenon are possible: (a) the physiographic and/or climatic characteristics as reported in the Eastwide Data Base and in the data layers used here may not adequately represent the physical characteristics found at forested plots; (b) the FIA sample plots are not well-distributed with respect to the range of climatic and physiographic conditions (i.e., there were too few plots at the extremes of climate or physiography); (c) some other physical variable, such as soil texture, soil water holding capacity, slope, or aspect, may better explain variation in biomass accumulation and wood production; or (d) the effects of management activities or the legacy of previous land use may overwhelm the impacts of physiographic and climatic characteristics on aboveground biomass and annual wood production. These alternative explanations represent hypotheses to be tested in future research.

It is important to note, however, that ecosystem process models have typically ignored the influences of management and land-use history on NPP (but see Aber and Driscoll (1997) and Aber *et al.* (1997)), instead using vegetation-type-specific algorithms driven by climate and physiography. Some modeling groups have even used "potential vegetation" to create NPP predictions (VEMAP Members 1995); our results suggest that the impacts of management and land-use history are critical to accurate predictions of both potential and actual growth rates in U.S. forests.

Next Steps

As we begin to consider the United States as a whole, considering seedling and shrub production (perhaps by using some of the FIA data not included in the Eastwide Data Base) will add completeness to these estimates. In addition, estimating belowground production will enable us to create more accurate predictions of overall C storage by forest systems. The utility of site-specific regression equations when applied to entire regions has been questioned; we will need to address this uncertainty as well. To determine the extent to which these estimates are representative of well-studied forests in the mid-Atlantic, we will compare these biomass and ANPP estimates to those developed and/or published by other researchers for study sites in the region. And, of course, we will compare these estimates to process model predictions to evaluate model accuracy. Finally, to quantify actual C stocks and fluxes for the region and the nation, we will need to expand our sample to include the entire set of FIA plots.

ACKNOWLEDGMENTS

We are especially grateful to Carol Alerich and Tom Frieswyk for their patience and assistance with the FIA database, to Yude Pan for sharing her climate and elevation data, and to Rachel Riemann for her help with geographic overlays. Scott Thomasma was instrumental in helping to debug the computer programs used to develop these estimates. Finally, we thank Linda Heath, John Aber, Marie-Louise Smith, and J. Morgan Grove for helpful discussions.

This paper was reviewed before publication by Will McWilliams, Forest Inventory and Analysis Unit, and James Steinman, Forest Health Monitoring Program, USDA Forest Service Northeastern Research Station, Radnor, PA, USA.

LITERATURE CITED

Aber, J.D.; Driscoll, C.T. 1997. Effects of land use, climate variation and N deposition on N cycling and C storage in northern hardwood forests. Global Biogeochemical Cycles. 11(4): 639-648.

Aber, J.D.; Ollinger, S.V.; Driscoll, C.T. 1997. Modeling nitrogen saturation in forest ecosystems in response to land use and atmospheric deposition. Ecological Modelling. 101: 61-78.

Barrett, J.; Jastrembski, J. 1990. Regional greenweight biomass equations for the Northeast. Northern Journal of Applied Forestry. 7: 187-189.

Birdsey, R.A. 1992. Carbon storage and accumulation in United States forest ecosystems. Gen. Tech. Rep. WO-59. Washington, DC: U.S. Department of Agriculture, Forest Service.

Birdsey, R.A.; Heath, L.S. 1995. Carbon changes in U.S. forests. In: Productivity of America's forests and climate change. Gen. Tech. Rep. RM-271. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

Birdsey, R.A.; Schreuder, H.T. 1992. An overview of forest inventory and analysis estimation procedures in the Eastern United States—with an emphasis on the components of change. Gen. Tech. Rep. RM-214. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station..

Brown, S.L.; Schroeder, P.E. 1998. Spatial patterns of biomass increment and mortality based on inventory data for eastern U.S. forests. Ecological Applications in review.

Gower, S.T.; McMurtrie, R.E.; Murty, D. 1996. Aboveground net primary production decline with stand age: Potential causes. Trends in Ecology and Evolution. 11(9): 378-382.

Hansen, M.H.; Frieswyk, T.; Glover, J.F.; Kelly, J.F. 1992. The eastwide forest inventory data base: users manual. Gen. Tech. Rep. NC-151. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station.

Jacobs, M.W.; Monteith, D.B. 1981. Feasibility of developing regional weight tables. Journal of Forestry. October: 676-677.

Jenkins, J.C.; Kicklighter, D.W.; Ollinger, S.V.; Aber, J.D.; Melillo, J.M. 1998. Sources of variability in NPP predictions at the regional scale: a comparison using PnET-II and TEM 4.0 in northeastern U.S. forests. Ecosystems in review.

Keys, J.J.; Carpenter, C.; Hooks, S.; Koenig, F.; McNab, W.; Russell, W.; Smith, M.-L. 1995. Ecological units of the eastern United States—first approximation (map, booklet of map unit tables, and CD-ROM with GIS coverages). Atlanta, GA: U.S. Department of Agriculture, Forest Service.

Marland, G.; Andres, R.; Boden, T. 1994. Trends '93: a compendium of data on global change. Oak Ridge, TN: Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory. ORNL/CDIAC-65.

McNab, W.; Avers, P. 1994. Ecological subregions of the United States: section descriptions. Admin. Publ. WO-WSA-5. Washington, DC: U.S. Department of Agriculture, Forest Service.

McNulty, S.G.; Vose, J.M.; Swank, W.T.; Aber, J.D.; Federer, C.A. 1994. Regional-scale forest ecosystem modeling: database development, model predictions and validation using a Geographic Information System. Climate Research. 4: 223-231.

Monteith, D. 1979. Whole tree weight tables for New York. AFRI Res. Rep. 40. Syracuse, NY: State University of New York College of Environmental Science and Forestry, Applied Forestry Research Institute.

Pan, Y.; Grove, J.; Hom, J.; Holt, H.; Jenkins, J.; Aber, J. 1998. Regional estimation and validation of forest production and water yield for Chesapeake Bay basin with PnET-II model and field data. Ecological Society of America Annual Meeting Abstracts. 83: 104.

Raich, J.W.; Rastetter, E.B.; Melillo, J.M.; Kicklighter, D.W.; Steudler, P.A.; Peterson, B.J. 1991. Potential net primary productivity in South America: application of a global model. Ecological Applications. 1: 399-429.

Ryan, M.G.; Yoder, B.J. 1997. Hydraulic limits to tree height and tree growth. BioScience. 47(4): 235-242.

Ryan, M.G.; Binkley, D.; Fownes, J.H. 1997. Age-related decline in forest productivity: pattern and process. Advances in Ecological Research. 27: 214-262.

Smith, D. 1986. The practice of silviculture. New York, NY: John Wiley & Sons.

VEMAP Members. 1995. Vegetation/ecosystem modeling and analysis project: comparing biogeography and biogeochemistry models in a continental-scale study of terrestrial ecosystem responses to climate change and CO2 doubling. Global Biogeochemical Cycles. 9(4): 407-437.

Wharton, E.H.; Alerich, A.L.; Drake, D.A. 1997. Estimating total forest biomass in New York, 1993. Resour. Bull. NE-139. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Wiant, H.V.J.; Sheetz, C.; Colaninno, A.; DeMoss, J.; Castaneda, F. 1977. Tables and procedures for estimating weights of some Appalachian hardwoods. Bull. 659T. Morgantown, WV: West Virginia University, Agricultural and Forestry Experiment Station, College of Agriculture and Forestry.

Young, H.E.; Ribe, J.H.; Wainwright, K. 1980. Weight tables for tree and shrub species in Maine. Misc. Rep. 230. Orono, ME: University of Maine Life Sciences and Agriculture Experiment Station.

Calibration of the STEMS Diameter Growth Model Using FIA Data

Veronica C. Lessard

Abstract.—The diameter growth model used in STEMS, the Stand and Tree Evaluation and Modeling System, was originally calibrated using data from permanent growth plots in Minnesota, Wisconsin, and Michigan. Because the model has been applied in predicting growth using Forest Inventory and Analysis (FIA) data, it was appropriate to refit the model to FIA data. The model was calibrated for four species—quaking aspen, balsam fir, paper birch, and red pine—using FIA data from the Aspen-Birch and Northern Pine Units of northeastern Minnesota. To compare the new and original calibrations of the model, it was important to use the same formulation and methodology in refitting the model. In this way differences due to the data sets would not be confounded with differences in model form or approach. Although STEMS was originally calibrated on permanent growth plot data, when applied to FIA data it produced estimates that were equivalent to those of the STEMS model that was refit to FIA data. Both models produced biased estimates that had large variation. Efforts to improve model performance should focus on improving the model form.

Inventories of forest stands and information about how these stands are growing are crucial elements for making wise forest management decisions. The Forest and Rangeland Renewable Resources Planning Act of 1974 and the McSweeney-McNary Forest Research Act of 1928 for the collection of forest inventory data were enacted by Congress to address the first of these elements. STEMS, the Stand and Tree Evaluation System (Belcher *et al.* 1982), is a system of models designed to meet the second element. STEMS was developed to analyze current forest resource information and to predict future resources levels. The STEMS tree growth model is composed of three components: (1) a potential diameter growth model that estimates the potential diameter growth of a tree; (2) a modifier model that reduces the potential diameter growth based on stand competition; and (3) a mortality model. Together the potential diameter growth and modifier models produce the predicted diameter growth of a tree.

Although the current STEMS diameter growth model has performed adequately (Guertin and Ramm 1996, Holdaway and Brand 1986), several concerns remain: (1) the potential and modifier models were calibrated as separate models, which makes reporting of confidence intervals for the mean predicted values intractable; (2) climate-related variables, which may improve precision of the predicted values, are not included in STEMS; (3) estimates of the variability of the predictor variables and their impact on the variability of the predictions of the model have not been analyzed; and (4) the current diameter growth model was originally calibrated on data from permanent growth plots, while many applications of the model have been on FIA data. These concerns are currently being addressed. First, Holdaway (2000) has developed a new model form, referred to as the Annual Forest Inventory System (AFIS) model, built on average growth and calibrated on FIA data as a single model, allowing confidence intervals to be reported. Second, although the AFIS model does not currently include climate-related variables, analysis for their incorporation is ongoing. Third, McRoberts (2000) has examined how uncertainty in the independent variables affects the precision of model predictions. He found that although inclusion of certain independent variables improves R^2 values for the model, the confidence band about the predicted values may be much wider as a result.

In this paper, the effect of the fourth of these concerns is investigated. The STEMS growth model, composed of the potential and modifier models, was initially calibrated on data from permanent growth plots from various locations in the Lake States (Michigan, Wisconsin, and Minnesota). Although it was the most complete Lake States data set available at the time, we now have complete coverage of the Lake States with repeated measurements of FIA data to calibrate the model on a data set similar to that on which the model is being applied. The objectives of this study are: (1) to calibrate the potential and modifier models for four species using FIA data from the northeast portion of Minnesota (MN FIA Units 1 and 2); and (2) to compare the bias and precision in predictions using the new versus the original calibrations of the STEMS growth model. The new and original calibrations of the STEMS growth model will be referred to as STEMS-FIA and STEMS, respectively, throughout the

---

Research Forester, USDA Forest Service, North Central Research Station, St. Paul, MN, USA.

rest of the paper. Because the purpose of the study is to see if the predictive ability of STEMS increases when applied to the FIA data set, no attempt was made to improve the model form, and the same methodology used to fit STEMS was used when fitting STEMS-FIA. In this way, differences due to the data set were not confounded with differences in model form or methodology. STEMS-FIA was calibrated for the following species: quaking aspen (*Populus tremuloides* Michx.), balsam fir (*Abies balsamea* (L.) Mill.), paper birch (*Betula papyrifera* Marsh.), and red pine (*Pinus resinosa* Ait.).

DATABASE

The original STEMS calibration used individual tree record data from permanent growth plots distributed across the Lake States. These plot records came from cutting experiments, demonstration woodlots, industrial, continuous forest inventory, and other records of forest growth. All plots were fixed size, ranging from 0.1 to 0.5 acres for square plots and 0.1 to 0.2 acres for circular plots. The minimum diameter at breast height (dbh) recorded on these plots ranged from 0.6 to 9 inches (Christensen *et al.* 1979).

FIA data for the STEMS-FIA diameter growth model came from land classified as forestland over all ownership categories in the Minnesota Aspen-Birch and Northern Pine Units (MN FIA Units 1 and 2). These data were systematically split into two data sets: 75 percent for calibration and 25 percent for validation. Inventory data were collected for trees of dbh greater than 5 inches on 10-point clusters using variable-radius point sampling, with a basal area factor (BAF) of 37.5 square feet per acre for the cluster. Data for trees 1 to 5 inches in diameter were obtained from 6.8-foot fixed-radius sample plots (approximately 1/300 acre) located at each point in the cluster. Before 1986, the fixed-radius plots were sampled at only the first three cluster points. Due to the sampling design, there were more trees of both the larger and smaller diameter classes for each species in the FIA data than in the original calibration data. Except for red pine, the total number of trees per species was greater in the FIA calibration database than in the permanent growth plot database (table 1). FIA data for the calibration of STEMS-FIA were extracted from undisturbed plots at two measurements. Only trees that were alive both at the beginning and end of the time interval were included. The first measurement for each plot in the data set was taken around either 1977 or 1990. The second measurement was recorded on the first subsequent date at which that plot was revisited. The average time interval was close to 9 years, with a range of approximately 2 to 21 years.

METHODS

The STEMS potential diameter growth (Hahn and Leary 1979) and corresponding modifier models (Holdaway 1984) were developed as species-specific, individual tree

Table 1.—*The number of trees in the databases used to calibrate STEMS. Data from the Lake States permanent growth plots were used in the original STEMS calibration, while Minnesota FIA data from the Aspen-Birch and Northern Pine Units (FIA Units 1 and 2, respectively) were used in the STEMS-FIA calibration.*

Species	**Number of trees of each species in each data set**	**Lake States permanent growth plots**	**MN FIA Unit 1**	**MN FIA Unit 2**	**MN FIA Units 1 & 2 Totals**
All species	All trees	51,149	34,225	25,822	60,047
Quaking aspen	All trees	2,547	8,190	7,193	15,383
Dominant and codominant trees	2,124 (83%)	7,028 (86%)	6,263 (87%)	13,291 (86%)	
Balsam fir	All trees	2,515	4,453	1,456	5,909
Dominant and codominant trees	1,277 (51%)	1,808 (41%)	607 (42%)	2,415 (41%)	
Paper birch	All trees	1,125	3,584	1,854	5,438
Dominant and codominant trees	748 (66%)	2,941 (82%)	1,561 (84%)	4,502 (83%)	
Red pine	All trees	NA	516	844	1,360
Dominant and codominant trees	11,663	452 (88%)	760 (90%)	1,212 (89%)	

based models to predict the increase in diameter for the Lake States tree species. The predicted average annual change in diameter for a tree is calculated as the product of its potential growth and a modifier based on the competition in the stand of which it is a member (Holdaway 1984). The potential diameter growth model portrays the growth rate that a tree of a given species could attain under optimal conditions. The modifier model accounts for stand competition. It is designed to allow a tree to reach a portion of the rate of growth predicted by the potential diameter growth model.

Potential Diameter Growth Model

The potential diameter growth represents an upper bound for the growth rate that may be attained by a tree of a given species based on its diameter (D), crown ratio (CR), and plot site index (SI). The following methods, used to develop the potential growth model (Hahn and Leary 1979), were followed as closely as possible when refitting the potential diameter growth model to FIA data. Only dominant and co-dominant trees were used in modeling the potential diameter growth model. Two measurements, approximately 10 years apart, were taken for each tree included in the database. The model uses average annual change in diameter (ΔD), calculated as the average positive difference in dbh measurements for trees within a cell on the two sampling dates divided by the number of years in the interval between measurements.

Site index was recorded in different ways for the permanent growth plot and FIA data sets. In the data set used for the STEMS calibration of the potential model, site index values for two species were generally recorded on a single sampling date. If the site index existed for the species being modeled, it was selected as the variable. Otherwise, the site index for another species was used. In the FIA data set, site index and site index species were recorded at each sampling date. The following rule was devised to handle site index when refitting the STEMS-FIA potential growth model:

1. If two different site index species are recorded on the two sampling dates and if one of these is the species of interest, use the site index for the species of interest.
2. If two different site index species are recorded on the two sampling dates and neither is the species of interest, take the average of the two site index values.
3. If the same site index species is recorded in both time periods, use the average of the two site index values.

As with the original STEMS calibration, the data for each species were grouped into cells by 1-inch diameter classes, 10-foot site index classes, and 10-percent crown ratio classes. The dependent variable (POT) for the potential diameter growth model was calculated as the mean plus 1.65 times the standard deviation of average annual diameter growth for trees in each cell ($\overline{\Delta D} + 1.65 s_{\Delta D}$). This diameter growth represents the 95th percentile of dominant and co-dominant diameter growth. To calculate a cell standard deviation for average annual diameter growth, at least two observations are needed per cell. If a cell contained a single tree, Hahn and Leary (1979) included it in "the most appropriate adjacent class." In the calibration of the STEMS-FIA potential model, three passes were made through the data to reassign single-observation trees to a new cell. At each pass, the value of one variable (SI, CR, or D) for the observation in cells containing a single tree was moved one class toward the center of the range of class values for that variable. After three passes, any remaining cells with single observations were dropped. The numbers of trees and cells used in fitting the STEMS and STEMS-FIA potential diameter growth models are given in table 2. The form of the potential diameter growth model (Hahn and Leary 1979) is:

$$\mathrm{POT} = b_1 + b_2 D^{b_3} + b_4 \mathrm{SI} \cdot \mathrm{CR} \cdot D^{b_5}, \qquad (1)$$

Marquardt's method of weighted nonlinear least squares regression was used to fit the model. The inverse of the squared standard error was used as the weighting scheme when fitting the STEMS-FIA potential model.

Modifier Model

The modifier model limits the predicted growth for trees by taking into account the competition within the stand (plot) surrounding each tree. The modifier model was calibrated on all trees of each species in the data set. The data set used to calibrate the STEMS modifier model was made up of two measurements, approximately 10 years apart, from undisturbed plots using trees that were alive at both measurements (Holdaway 1984).

In keeping with the methodology used for the original calibration of STEMS, the modifier value (MOD) for each tree is calculated as the ratio of the actual observed growth to the potential growth for that tree calculated by (1). Data were sorted by the independent variables into 2-inch average stand diameter (AD) classes, 25-ft^2 basal area (BA) classes, and 10-percent relative diameter (REL), the ratio of individual tree dbh to AD, classes. The cell mean modifier value was used as the dependent variable in fitting the nonlinear modifier model. The resulting number of cells used to calibrate the modifier on FIA data is given in table 2.

Table 2.—*The number of trees and number of cells used in calibrating the potential diameter growth and modifier models for the four species are given in the table below. The number of cells used in the original calibration of the modifier model is not available in the literature.*

Model	Species	STEMS		STEMS-FIA	
		Trees	Cells	Trees	Cells
		- - - - - - - - -	*Number*	- - - - - - - - -	
Potential					
	Balsam fir	1,277	121	2,376	387
	Quaking aspen	2,124	201	13,256	576
	Paper birch	748	112	4,467	426
	Red pine	11,663	282	1,177	239
Modifier					
	Balsam fir	4,376	NA	5,909	773
	Quaking aspen	2,944	NA	15,383	1,209
	Paper birch	1,214	NA	5,438	884
	Red pine	6,067-N[1] 20,224-P[1]	NA	1,360	579

[1] N and P denote natural stands and plantations of red pine, respectively. Because so few red pine trees existed in the MN FIA Units 1 and 2 data set, red pines were not separated by this distinction.

The form of the modifier model is (Holdaway 1984):

$$\mathrm{MOD} \;=\; 1 - \exp\{-\mathrm{f(REL)}\cdot \mathrm{g(AD)}\cdot[(\mathrm{BA}_{\max} - \mathrm{BA})/\mathrm{BA}]^{\frac{1}{2}}\} \qquad (2)$$

where

$$\mathrm{f(REL)} \;=\; b_1\,[1 - \exp(b_2\cdot \mathrm{REL})]^{b_3} + b_4\,, \qquad (3)$$

and

$$\mathrm{g(AD)} \;=\; c_1\,(AD+1)^{c2} \quad . \qquad (4)$$

In keeping with the methodology used in the original calibration, the nonlinear modifier model was fit in two steps. First, parameter values, c_1 and c_2, were obtained for g(AD) by fitting equation 2, while setting f(R) = 1.0. These parameter values were substituted into (2), and equation 2 was refit to obtain values for the four parameters in equation 3. At both steps Marquardt's method of nonlinear regression, weighted by the number of observations per cell, was used.

Verification and Validation

The models were verified in separate runs of the STEMS growth projection system using the parameters of the STEMS and STEMS-FIA growth and modifier models on the calibration data. The two models were evaluated on their ability to predict tree diameter and basal area per acre growth when applied to the data set on which STEMS-FIA was calibrated. The STEMS and STEMS-FIA growth models were then tested for their performance on the validation data.

The STEMS growth projection system contains adjustments applied to the STEMS. The adjustment factors are ratio of means multipliers, calculated for each of five dbh classes, to adjust the growth predictions of this regional STEMS model for local conditions (Holdaway 1985, Smith 1983). Because STEMS-FIA was calibrated on local data (MN FIA Units 1 and 2), the adjustment factors were not applied to the STEMS-FIA potential growth model when running the STEMS system to predict diameter and basal area per acre growth. The adjustments were applied to the STEMS model when predicting diameter and basal area per acre growth.

Using the calibration and validation data sets in separate runs, each tree was grown for the number of years in the interval between its first and second measurement. The residuals, calculated as the observed minus predicted dbh for each tree (or stand basal area per acre for each plot), were annualized by dividing by the number of years in the interval over which each tree or plot was grown. Shapiro-Wilk ($n < 2000$) and Kolmogorov ($n \geq 2000$) tests of normality conducted on the sets of annualized residuals from both diameter and stand basal area predictions indicated that most of these data sets were not normally distributed. Annualized residual medians, median ratios, size ratios, standard deviations, and r^2 values were calculated to examine the prediction differences in diameter and stand basal area growth by species for

Table 3.—*The median annualized diameter prediction residuals (inches/year) are given for the STEMS and STEMS-FIA diameter growth models. Negative values for residuals and median ratios indicate an overprediction by the model.*

Species	Model	Number of trees	Median residual	Standard deviation	Median ratio	Size ratio	Wilcoxon $H_0{:}M_i=0$	Wilcoxon $H_0{:}M_1=M_2$	Box's test $H_0{:}\sigma_1^2=\sigma_2^2$	r^2
			- - - In/yr - - -		- Percent -		- - - - - P-value - - - - -			
CALIBRATION										
Red pine	STEMS	1,360	-0.009	0.0696	-7.0	32.7	0.0028			0.418
Red pine	STEMS-FIA	1,360	-0.005	0.0689	-3.9	30.3	0.2007	0.1533	0.9695	0.437
Balsam fir	STEMS	5,909	-0.011	0.0620	-13.8	47.5	0.0001			0.199
Balsam fir	STEMS-FIA	5,909	-0.008	0.0573	-10.0	41.3	0.0001	0.0022	0.0540	0.304
Quaking aspen	STEMS	15,383	-0.006	0.0703	-4.8	35.2	0.1148			0.157
Quaking aspen	STEMS-FIA	15,383	-0.004	0.0717	-3.2	34.4	0.4224	0.4757	0.1786	0.172
Paper birch	STEMS	5,461	-0.007	0.0496	-11.4	48.8	0.0001			0.101
Paper birch	STEMS-FIA	5,461	-0.006	0.0486	-9.8	47.1	0.0001	0.3089	0.5688	0.117
VALIDATION										
Red pine	STEMS	501	0.004	0.0796	3.1	31.9	0.0561			0.480
Red pine	STEMS-FIA	501	0.006	0.0721	4.7	29.6	0.0085	0.6247	0.0969	0.560
Balsam fir	STEMS	1,924	-0.012	0.0656	-16.0	50.7	0.0001			0.201
Balsam fir	STEMS-FIA	1,924	-0.011	0.0599	-14.7	43.3	0.0001	0.0495	0.0722	0.328
Quaking aspen	STEMS	5,348	-0.005	0.0708	-4.2	35.8	0.4931			0.133
Quaking aspen	STEMS-FIA	5,348	-0.003	0.0724	-2.5	35.0	0.3731	0.1626	0.1163	0.156
Paper birch	STEMS	1,708	-0.005	0.0672	-7.9	48.7	0.1056			0.066
Paper birch	STEMS-FIA	1,708	-0.005	0.0665	-7.9	50.3	0.0997	0.9686	0.8187	0.074

[1] To calculate the size ratios (percent), the absolute values of annualized growth residuals and annualized observed growth were taken. The median values for each were foun,d and the ratio of the median annual residual magnitude to the median annual observed growth magnitude was multiplied by 100 percent. Median ratios (percent) were calculated as 100 percent times the ratio of the median annualized residual to the median annual observed growth magnitude. One-sample Wilcoxon Signed Rank tests were used to test if the median residual was different from zero (*a* = 0.05). Two-sample Wilcoxon Rank Sum (Mann-Whitney-Wilcoxon) tests were used to test if the median residual of STEMS-FIA was different from that of STEMS (*a* = 0.05). Box's test was used to test for homogeneity in residual variances of STEMS-FIA and STEMS (*a* = 0.10). The r^2 values were computed as the square of the correlation coefficient between the observed and predicted annual diameter growth.

STEMS and STEMS-FIA (tables 3 and 4). Median ratios present the median bias as a percent of the magnitude of observed growth and give a perspective of the importance of this bias from a biological standpoint. By contrast, the size ratios give a biological perspective to the size of the residuals relative to the size of actual growth. Median ratios are calculated as 100 percent times the ratio of the median annualized growth residual to the median of absolute values of annualized observed growth. To calculate the size ratios, the absolute values of annualized growth residuals and annualized reserved growth were taken. The median values for each were found, and the ratio of the median growth residual to the median observed growth was multiplied by 100 percent. The r^2 values are calculated as the square of the coefficient of correlation between the annualized predicted and observed values of diameter or basal area per acre growth. The Wilcoxon Signed Rank one-sample test was used to test if the prediction residuals for each model were significantly different from zero. Two-sample Wilcoxon Rank Sum (Mann-Whitney-Wilcoxon) tests were used to test for overall differences between the annualized prediction residuals of STEMS-FIA and STEMS. Box's test was used to test for differences in the precision of STEMS-FIA and STEMS.

RESULTS

Verification

DBH Estimates

Both models were applied to the data set used to calibrate STEMS-FIA. In general, STEMS-FIA performed as well or better than STEMS, the regional model with local adjustments. When using the calibration data, both STEMS-FIA and STEMS generally overpredicted dbh growth. The magnitude of the median residual values by

Table 4.—*The median annualized stand basal area per acre (feet²/acre/year) prediction residuals are given for the STEMS and STEMS-FIA diameter growth models. Negative values for residuals and median ratios indicate an overprediction by the model.*

Species	Model	Number of plots	Median residual	Standard deviation	Median ratio	Size ratio	Wilcoxon H_0:M_i=0	Wilcoxon H_0:M_1=M_2	Box's test H_0:σ_1^2=σ_2^2	r^2
			- - *ft²/ac/yr* - -		- *Percent* -		- - - - - *P-value* - - - - -			
CALIBRATION										
Red pine	STEMS	62	0.097	2.0590	5.2	48.6	0.9503			0.588
Red pine	STEMS-FIA	62	0.003	1.9723	0.2	44.5	0.7843	0.8710	0.5982	0.621
Balsam fir	STEMS	228	-0.505	1.8993	-41.7	83.0	0.0001			0.395
Balsam fir	STEMS-FIA	228	-0.386	1.9344	-31.8	76.4	0.0001	0.6074	0.9558	0.370
Quaking aspen	STEMS	1,296	-0.297	2.0160	-22.8	75.1	0.0001			0.512
Quaking aspen	STEMS-FIA	1,296	-0.281	2.1004	-21.6	82.3	0.0001	0.4379	0.2606	0.471
Paper birch	STEMS	247	-0.375	1.7699	-35.0	104.8	0.0011			0.169
Paper birch	STEMS-FIA	247	-0.351	1.7336	-32.8	102.0	0.0002	0.8249	0.9807	0.177
VALIDATION										
Red pine	STEMS	25	0.497	1.5805	26.2	40.4	0.0340			0.836
Red pine	STEMS-FIA	25	0.285	1.3085	15.0	85.5	0.0523	0.7124	0.4117	0.888
Balsam fir	STEMS	62	0.046	2.2645	2.9	68.2	0.6398			0.282
Balsam fir	STEMS-FIA	62	0.054	2.2393	3.4	67.6	0.6649	0.9641	0.8614	0.288
Quaking aspen	STEMS	443	-0.293	1.9084	-24.4	82.0	0.0003			0.483
Quaking aspen	STEMS-FIA	443	-0.327	2.0027	-27.2	78.5	0.0015	0.7850	0.4653	0.424
Paper birch	STEMS	71	-0.466	1.9104	-40.1	81.6	0.0215			0.221
Paper birch	STEMS-FIA	71	-0.391	1.8684	-33.7	91.1	0.0075	0.8736	0.8494	0.234

[1] To calculate the size ratios (percent), the absolute values of annualized growth residuals and annualized observed growth were taken. The median values for each were found, and the ratio of the median annual residual magnitude to the median annual observed growth magnitude was multiplied by 100 percent. Median ratios (percent) were calculated as 100 percent times the ratio of the median annualized residual to the median annual observed growth magnitude. One-sample Wilcoxon Signed Rank tests were used to test if the median residual was different from zero (*a*= 0.05). Two-sample Wilcoxon Rank Sum (Mann-Whitney-Wilcoxon) tests were used to test if the median residual of STEMS-FIA was different from that of STEMS (*a* = 0.05). Box's test was used to test for homogeneity in residual variances of STEMS-FIA and STEMS (*a* = 0.10). The r² values were computed as the square of the correlation coefficient between the observed and predicted annual diameter growth

species and model ranged from 0.004 to 0.011 inches per year (table 3). These overpredictions were greater than zero ($P < 0.05$) for both STEMS-FIA and STEMS for balsam fir ($P = 0.0001$) and paper birch ($P = 0.0001$) and for STEMS for red pine ($P = 0.0028$). For those median residuals found to be different from zero, the corresponding median ratio values ranged from -7.0 to -13.8 percent. The median residuals were greater in magnitude for STEMS than for STEMS-FIA over all species.

To test if the differences in residuals for STEMS-FIA and STEMS were significant, two-sample Wilcoxon Rank Sums tests were used on all four species. The balsam fir annualized residuals were different ($P = 0.0022$) for the two models. STEMS overestimated dbh by a median value of 0.011 inches per year, while STEMS-FIA overestimated dbh by a median value of 0.008 inches per year. This difference, approximately 0.03 inches over a 10-year prediction period, is relatively small from a biological viewpoint. The differences in the dbh residuals of the two models were not statistically significant for the other species.

The size ratios, each given as the percent of the median observed growth magnitude represented by the median growth residual magnitude, ranged from 30.3 to 48.8 percent. The values of r^2 were highest for red pine (0.418 and 0.437) and lowest for paper birch (0.101 and 0.117) for STEMS and STEMS-FIA, respectively. In all cases, the r^2 value was at least as high for STEMS-FIA as it was for STEMS, although again all r^2 values were low.

The variance of dbh estimates from the two models was compared using Box's test at a 0.10 level of significance. The variation of balsam fir growth residuals was different between the two models ($P = 0.0540$). The standard deviation of balsam fir dbh residuals was 0.0573 inches for STEMS-FIA and 0.0620 inches for STEMS. No differences in variance for the diameter residuals were found for the other species.

Basal Area Per Acre Estimates

The two models overestimated annual basal area per acre for balsam fir (P = 0.0001), quaking aspen (P = 0.0001), and paper birch (P = 0.0011 and P = 0.0002 for STEMS and STEMS FIA, respectively) by median values ranging from 0.281 to 0.505 ft^2 per acre per year (table 4). The median ratios for overprediction for these three species ranged from 21.6 to 41.7 percent, while the corresponding size ratios ranged from 75.1 to 104.8. As with diameter, the correlation between predicted and observed basal area growth was highest for red pine, with r^2 values of 0.588 and 0.621, and lowest for paper birch, with r^2 values of 0.169 and 0.177 for STEMS and STEMS-FIA, respectively. The r^2 values for STEMS were slightly higher than those for STEMS-FIA in balsam fir and quaking aspen, but lower in red pine and paper birch. No differences were found between the median residuals for the predictions of basal area per acre for any of the species (Wilcoxon Signed Rank, (a = 0.05). The variation of the basal area per acre growth residuals was equivalent for both models in all four species (Box's test, (a = 0.10).

Validation

Dbh Estimates

Validation is used to test model performance on a data set similar to, but separate from the data with which the model was calibrated. Both STEMS-FIA and STEMS were applied to the validation data to compare performance. The models overestimated average annual dbh growth in balsam fir by median values of 0.012 and 0.011 inches and median ratios of 16.0 and 14.7 percent for STEMS (P = 0.0001) and STEMS-FIA (P = 0.0001), respectively (table 3). In red pine, STEMS-FIA underestimated average annual change in dbh by a median value of 0.006 inches (P = 0.0085) and a median ratio of 4.7 percent, while STEMS underestimated it by a median value of 0.004 inches (P = 0.0561) and a median ratio of 3.1 percent. The size ratios for all four species ranged from 29.6 percent for the STEMS FIA prediction residuals for red pine to 50.7 percent for the STEMS prediction residuals for balsam fir. Again, the correlation between the predicted and observed diameter growth for the interval was highest for red pine, with r^2 values of 0.480 and 0.560, and lowest for paper birch, with r^2 values of 0.066 and 0.074 for STEMS and STEMS-FIA, respectively. There was a difference in residuals of the two models only in balsam fir (P = 0.0495), but this difference is only about 0.01 inches over a 10-year projection period. There was a difference in variance of the residuals for STEMS and STEMS-FIA only in red pine (Box's test; P = 0.0969) and balsam fir (Box's test; P = 0.0722). In both cases, the standard deviation for STEMS was greater than for STEMS-FIA.

Basal Area Per Acre Estimates

Both STEMS and STEMS-FIA overestimated average annual stand basal area per acre change by median values of 0.293 and 0.327 ft^2 per acre for quaking aspen (P = 0.0003 and P = 0.0015) and by 0.466 and 0.391 ft^2 per acre for paper birch (P = 0.0215 and P = 0.0075), respectively (table 4). STEMS underestimated annual basal area per acre change by a median value of 0.497 square feet (P = 0.0340) in red pine. The models overestimated basal area growth for quaking aspen and paper birch by median ratio values between 24.4 to 40.1 percent and underestimated annual basal area per acre growth for red pine by median ratio values of 26.2 and 15.0 percent for STEMS and STEMS FIA, respectively. The size ratios ranged from 40.4 percent for the STEMS residuals for red pine to 91.1 percent for the STEMS-FIA residuals for paper birch. The r^2 values were highest for red pine (0.836 and 0.888 for STEMS and STEMS-FIA, respectively). For balsam fir, quaking aspen, and paper birch, the r^2 values ranged from 0.221 to 0.483. No differences were found in either medians or variation of residuals for the two models within any species (table 4).

CONCLUSIONS

In general, the performances of STEMS-FIA and STEMS in predicting annual diameter and basal area change were nearly equivalent. The direction of overprediction or underprediction was the same for the two models within a species of a data set. While there is very little difference in the predictive ability of the two models, the bias of both diameter and basal area per acre growth predictions, the relative size of these residuals, and the lack of fit indicated by the low r^2 values are causes for concern with both models.

Although STEMS was calibrated on permanent growth data, when applied to FIA data it performs about as well as STEMS-FIA. While the model form appears to be robust in the sense that results from different estimation procedures are equivalent, the model form is limiting in the sense that it does only so well. There seems to be no need to try to refine STEMS through further recalibration. Future work should focus on improving the form of model and possible inclusion of climate-related variables (Holdaway 2000).

ACKNOWLEDGMENTS

The author wishes to thank Margaret R. Holdaway for her help and suggestions in sorting through the process of calibrating the STEMS growth model in a way most closely resembling the way it had originally been done and to the Lake States Alliance for their support of this research.

The following people have reviewed this manuscript: David D. Reed, Michigan Technological University, Houghton, MI, USA; Margaret R. Holdaway and Ronald E. McRoberts, USDA Forest Service, North Central Research Station, St. Paul, MN, USA.

LITERATURE CITED

Belcher, David M.; Holdaway, Margaret R.; Brand, Gary J. 1982. A description of STEMS. The stand and tree evaluation and modeling system. Gen. Tech. Rep. NC-79. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 18 p.

Christensen, Linda; Hahn, Jerold T.; Leary, Rolfe A. 1979. Data Base. In: A generalized forest growth projection system applied to the Lake States region. Gen. Tech. Rep. NC-49. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 16-21.

Guertin, Patrick J.; Ramm, Carl W. 1996. Testing Lake States TWIGS: five-year growth projections for upland hardwoods in northern Lower Michigan. Northern Journal of Applied Forestry. 13(4): 182-188.

Hahn, Jerold T.; Leary, Rolfe A. 1979. Potential diameter growth functions. In: A generalized forest growth projection system applied to the Lake States region. Gen. Tech. Rep. NC-49. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 22-26.

Holdaway, Margaret R. 1984. Modeling the effect of competition on tree diameter growth as applied in STEMS. Gen. Tech. Rep. NC-94. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 9 p.

Holdaway, Margaret R. 1985. Adjusting STEMS growth model for Wisconsin forests. Res. Pap. NC-267. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 8 p.

Holdaway, Margaret R. 2000. The AFIS tree growth model for updating annual forest inventories in Minnesota. In: Hansen, M., Burk, T., eds. Integrated tools for natural resources inventories in the 21st century. Proceedings of the IUFRO conference; 1998 August 16-20; Boise, ID. Gen. Tech. Rep. NC-212. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 507-514.

Holdaway, Margaret R.; Brand, Gary J. 1986. An evaluation of Lake States STEMS85. Res. Pap. NC-269. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 10 p.

McRoberts, Ronald E. 2000. Comparing the STEMS and AFIS growth models with respect to the uncertainty of predictions. In: Hansen, M., Burk, T., eds. Integrated tools for natural resources inventories in the 21st century. Proceedings of the IUFRO conference; 1998 August 16-20; Boise, ID. Gen. Tech. Rep. NC-212. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 539-548.

Smith, W. Brad. 1983. Adjusting the STEMS regional forest growth model to improve local predictions. Res. Note NC-297. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 5 p.

A Survival Model for Individual Shortleaf Pine Trees in Even-Aged Natural Stands

Thomas B. Lynch, Michael M. Huebschmann, and Paul A. Murphy

ABSTRACT.—A model was developed that predicts the probability of survival for individual shortleaf pine (*Pinus echinata* Mill.) trees growing in even-aged natural stands. Data for model development were obtained from the first two measurements of permanently established plots located in naturally occurring shortleaf pine forests on the Ouachita and Ozark National Forests in western Arkansas and eastern Oklahoma. The logistic function was used to model survival probability. Parameters were estimated by using logistic regression in which the dependent variable was "1" for trees alive during both inventories and "0" for trees that died prior to the second inventory. Examination of several combinations of independent variables (representing tree size, relative position of the tree in the stand, stand density, and stand age) yielded the following model:

$$POS = (1 + \exp(-(b_0 + b_1/DR + b_2SBA + b_3DH)))^{-1}$$

where POS is annual probability of survival, DR is the ratio of quadratic mean diameter to individual tree dbh, SBA is stand basal area in square feet per acre, DH is average height of dominant and codominant trees in feet, b_0, b_1, b_2, b_3 are parameter estimates. A chi-square evaluation was performed to test model performance. This tree survival model is being used to estimate probability of individual tree survival in a distance-independent individual tree simulator for shortleaf pine.

A survival model is an integral part of the ShortLeaf Pine Stand Simulator (SLPSS) (Huebschmann *et al.* 1998), an individual tree model that has been developed for even-aged natural shortleaf pine forests. Other components of the model include an individual tree basal area growth model (Hitch 1994) and a compatible height prediction and projection system for shortleaf pine trees in even-aged natural stands (Lynch and Murphy 1995). Hamilton (1974) proposed that the following logistic equation be used to model probability of individual tree mortality:

$$P = \left[1 + \exp(-(\beta_0 + \sum_{i=1}^{m} \beta_i x_i)\right]^{-1} + \varepsilon \qquad (1)$$

where P is probability of mortality, x_i are independent variables, β_0 and β_i are parameters, and ε is an error term with mean zero. Hamilton (1974) suggested that parameters in the model be estimated by logistic regression in which the dependent variable is assigned "0" for trees surviving a designated time interval and "1" for trees dying in the interval. Modelers who wish to predict probability of mortality designate mortality trees as "1" and surviving trees as "0," while modelers who wish to predict probability of survival designate surviving trees as "1" and mortality trees as "0." The logistic regression procedure would minimize the sum of squared errors between the dependent variable and model predictions. Predictions are constrained by the logistic model form to range between 1 and 0 so that they may be interpreted as mortality probabilities. Hamilton modified the "RISK" program developed by Walker and Duncan (1967) to accomplish parameter estimation. Hamilton and Edwards (1976) applied this methodology to mortality modeling for several tree species in northern Idaho. They used the SCREEN program (Hamilton and Wendt 1975) to identify potentially important independent variables. Among the variables they used to predict probability of mortality were dbh, height, age, crown class, and basal area per acre. Many other individual tree growth and yield systems use this or a very similar method to estimate probability of mortality or survival. Amateis *et al.* (1989) and Daniels and Burkhart (1975) fitted parameters to a survival model by assigning "1" as the dependent variable for surviving trees and "0" as the dependent variable for mortality trees, but they did not use the logistic model form as the prediction equation.

The authors are Associate Professor (telephone 405-744-5447, FAX 405-744-9693 email: tlynch@okway.okstate.edu) and Senior Research Specialist, Department of Forestry, OSU, Ag Hall Room 008C, Stillwater, OK 74078-6013, USA; and Research Forester, Southern Research Station, University of Arkansas at Monticello, P.O. Box 3516, UAM Monticello, AR 71656-3516, USA.

Most growth and yield information on naturally occurring shortleaf pine stands has been based on stand-level tables or equations that do not include models for probability of survival of individual trees. USDA Misc. Publ. 50 (USDA Forest Service 1929) contains normal yield tables for fully stocked natural stands of shortleaf pine. Schumacher and Coile (1960) provide yield tables for shortleaf pine based on 74 well-stocked temporary plots in the North Carolina Piedmont, which are also based on a normal stocking concept. Brinkman (1967) developed shorteaf pine stand volume equations based on periodic remeasurements in 57 stands. Data obtained from the Southern Research Station Forest Inventory and Analysis unit are the basis of stand-level growth and yield models for natural shortleaf pine stands developed by Murphy and Beltz (1981) and Murphy (1982), which can be applied to a variety of stand densities. Lynch *et al.* (1991) developed stand volume equations for shortleaf pine. Murphy and Farrar (1985) developed a stand-level growth and yield system for uneven-aged shortleaf pine forests. Growth and yield information for shorteaf pine stands can be obtained from the central states version of TWIGS (Miner *et al.* 1989), an individual tree simulator that uses equations developed with inventory data from Indiana, Illinois, and Missouri. Central states TWIGS does contain individual tree mortality models. An individual tree simulation system for forests in the south that provides information on shortleaf pine has been developed by Bolton and Meldahl (1990).

DATA

Prior to 1985, most sources of growth and yield information for naturally occurring shortleaf pine stands were based on fully stocked plots representing a limited range of densities (normal stocking) or on inventory data that primarily represented unmanaged stands. Therefore, in 1985, a cooperative study between the USDA Forest Service Southern Research Station at Monticello, Arkansas, and the Department of Forestry at Oklahoma State University (hereafter termed the OSU-Forest Service Co-op study) was initiated to establish growth and yield plots in even-aged natural shortleaf pine stands representing a range of ages, densities, and site qualities. These data were used to develop a shortleaf pine survival model. The study plan consisted of four levels of age (20, 40, 60, and 80 years), four levels of base age 50 site index (<56, 60, 70, and >75 feet), and four levels of basal area per acre (30, 60, 90, and 120 square feet per acre). The original plan specified establishment of three plots in each combination of age, site index, and density for a total of 192 plots. Only 191 of these were established. Some were lost due to a wind storm and failure to execute thinning treatments at some locations, so 183 plots remained at the second measurement. Plots were established during 1985 to 1988 and remeasured from 1990 to 1992, with intervals of 4 or 5 years between measurements.

A 33-foot circular buffer strip surrounds a 0.2-acre measurement plot at each plot location. The measurement plot and buffer strip were thinned from below to the same residual basal area per acre level and received the same chemical herbicide control treatment for competing vegetation. Within the 0.2-acre plot all shortleaf pine trees 1 inch in dbh or larger were numbered, marked at the dbh measurement point, and the dbh, crown class, distance to plot center, and azimuth from plot center were recorded. A representative sample of trees within each dbh class on the plot was selected for measurement of total height and height to live crown. Each dominant or codominant tree on every plot was cored with an increment borer to determine age. Site index curves developed by Graney and Burkhart (1973) were used to estimate the base age 50 year site index on each plot.

Thirty-four plots were available from a shortleaf pine thinning study established by Frank Freese during 1963-1964. Each plot consisted of a 0.2-acre measurement plot, and each was originally thinned to a basal area of 45, 65, 85, 105, or 125 square feet per acre. By combining plots from the OSU-Forest Service Co-op study with plots from the Freese study, a total of 217 plots were available for development of a mortality model for individual shortleaf pine trees. All plots in the OSU-Forest Service Co-op study were established on the Ouachita or Ozark National Forests. Although some of the Freese study plots were established on industrial forest ownerships, all remaining plots are located on the Ouachita National Forest. Plot locations range from the Boston Mountains near Russellville, Arkansas, in the Ozark National Forest to the West Gulf Coastal Plain in the Ouachita National Forest near Broken Bow, Oklahoma. Most plots are located in the Ouachita Mountain region of eastern Oklahoma and western Arkansas. Table 1 provides a summary of the plot-level data used for analysis. A summary of the data at the individual tree level is given in table 2.

MODEL DEVELOPMENT

Data from individual shortleaf pine trees were used to fit parameters to a logistic survival model having the general form of equation 1. To assess variables potentially useful for prediction of survival probabilities, the SCREEN program (Hamilton and Wendt 1975) was run on the shortleaf pine data set. Among variables considered were dbh, quadratic mean dbh (QMD), ratio of QMD to dbh, site index, crown ratio, average height of dominant and codominant trees, age, plot basal area per acre, and proportion of basal area in trees as large or larger than the tree for which survival is to be predicted.

Table 1.—*Summary statistics for 217 shortleaf pine growth study plots*

Variable	Mean	Std. dev.	Minimum	Maximum
Initial basal area (ft²/acre)	81.88	35.07	27.32	174.24
Final basal area (ft²/acre)	93.04	37.91	14.87	180.00
Mid-period basal area (ft²/acre)	87.46	36.24	22.53	177.12
Initial age (years)	55.2	18.7	18	93
Final age (years)	60.3	18.7	23	99
Site index, height at age 50 (ft)	62.2	10.7	38.9	87.1

Table 2.—*Mean, standard deviation, minimum and maximum for dbh, quadratic mean dbh (QMD), and ratio of QMD to dbh from 9,238 individual shortleaf pine trees used to fit parameters to a logistic survival model*

Variable	Mean	Std. dev.	Minimum	Maximum
QMD (in.)	7.70	3.31	3.10	17.90
Dbh (in)	7.51	3.73	1.1	24.4
Ratio QMD to dbh	1.10	0.33	0.44	4.42

For fitting parameters to equation 1, the dependent variable for each individual tree was coded as "1" if the tree survived the measurement interval and "0" if the tree did not survive the measurement interval. It was desired to obtain a model that would predict survival on an annual basis for use in an individual tree growth model that uses annual steps. Since plot measurement intervals in the shortleaf pine data were either 4 or 5 years, the following transformation discussed by Hamilton and Edwards (1976) was used to fit parameters on an annual basis:

$$P_t = \left[1 + \exp(-(\beta_0 + \sum_{i=1}^{m} \beta_i x_i))\right]^{-t} + \varepsilon \qquad (2)$$

where t is the length of the measurement period in years, P_t is the probability of survival for time period t, and other symbols are as defined for equation 1. Nonlinear weighted regression was used to fit parameters. The weight used was $1/(P(1-P))$, which is the inverse of the variance of a Bernoulli (1 or 0) random variable. Trials were run using both the RISK program (Hamilton 1974) and SAS PROC NLIN (SAS Institute 1988) with similar results. Various models with various combinations of independent variables were evaluated. The model resulting from this evaluation process is:

$$POS = (1 + \exp(-(b_0 + b_1/DR + b_2SBA + b_3DH)))^{-1} \qquad (3)$$

where POS is annual probability of survival, DR is the ratio of quadratic mean diameter to individual tree dbh, SBA is stand basal area in square feet per acre, DH is average height of dominant and codominant trees in feet, and b_0, b_1, b_2, b_3 are parameter estimates. Initially, the data were divided into two subsets, one for fitting parameters and a randomly selected independent data set used for model evaluation. After selection of model 3, the two subsets were combined and used to obtain final parameter estimates. These estimated parameter values, together with their standard errors, are given in table 3. Ratios of parameter estimates to standard errors show values of t=12.2 for b_1 ($1/DR$) and t=4.9 for b_2 (SBA), both of which are significant at the α=0.05 level. It might be expected that for a given QMD, trees having a smaller dbh resulting in a larger value of the ratio DR = QMD/dbh would have a smaller chance of survival, while trees in stands having a lower basal area per acre would have a greater chance of survival. The signs of the coefficients b_1 ($1/DR$) and b_2 (SBA) in the context of equation 3 are consistent with these expectations. The average height of dominants and codominants DH was calculated by evaluating the site index curves of Graney and Burkhart (1973) at plot age and site index. The coefficient associated with DH, b_3, has t=-1.4, which would be significant

Table 3.—*Parameter estimates for a logistic model of survival probability for individual shortleaf pine trees*

Coefficient	Estimate	Standard error
b_0	2.912370652	0.44483029972
b_1	4.789284600	0.39415378476
b_2	-0.015129972	0.00310011084
b_3	-0.006680302	0.00465072624

at the α=0.16 level but is not significant at the α =0.05 level. Still, it was decided that significance was high enough to be beneficial for predictions. *DH* is a function of site quality and age, so it reflects the influence of both of these variables.

MODEL EVALUATION

A chi-square test was proposed by Hamilton and Edwards (1976) for evaluation of mortality models based on logistic regression. Hamilton (1974) showed why the mean square error, often used to evaluate regression models, is not appropriate for evaluation of logistic regression with a Bernoulli (0 or 1) dependent variable. Neter *et al.* (1989) recommend the following chi-square statistic for evaluation of logistic regression models:

(4)

where c is the number of categories, O_{jk} is the prediction for "success" ("1") in category j when k=1, and for "failure" ("0") in category j when k=0. When applied to individual tree survival models, a natural categorization makes c the number of dbh classes, with O_{j1} the number of surviving trees in class j and O_{j0} the number of mortality trees in dbh class j. E_{j1} is obtained by summing the individual predicted probabilities of survival for trees in dbh class j, while E_{j0} is found by summing the individual predicted probabilities of mortality for trees in dbh class j.

Neter *et al.* (1989) recommend comparison of X^2 to a tabulated value of the chi-square distribution χ^2 with $c-2$ degrees of freedom. Hosmer and Lemeshow (1980) showed through simulation studies that two degrees of freedom should be subtracted from the number of categories when evaluating the logistic regression model with chi-square computed on the data set used for parameter fitting (see also Hosmer and Lemeshow 1989).

Comparisons between observed and predicted number of surviving and mortality trees are given in table 4. Predicted survival is obtained by summation of equation 3 for all trees within the indicated dbh class. Probability for mortality can be obtained by subtracting the survival prediction from 1. These mortality predictions are used to obtain predicted mortality for each dbh class in table 4. Since the plot data are based on measurement intervals of 4 and 5 years, survival probabilities were obtained by raising equation 3 to the power of the number of years in the measurement period, as indicated in equation 2. Thus, the values in table 4 do not represent annual survival or mortality rates; rather, they are a mixture of 4- and 5-year rates. Chi-square values for survival and mortality corresponding to each dbh class are also given in table 4. The computed chi-square for model evaluation according to equation 4 can be obtained by summation of chi-square components corresponding to each dbh class in table 4:

$$X^2 = 2.0364 + 57.1077 = 59.1441$$

Table 4.—*Predicted and actual survival and mortality by dbh class with chi-square contribution, based on measurement intervals of 4 and 5 years*

Dbh class	**No. trees**	**No. surv. trees**	**Predicted survivors**	**Chi-square**	**No.mort. trees**	**Predicted mortality**	**Chi-square**
1	24	19	19.09	0.0004	5	4.91	0.0016
2	443	391	398.79	0.1520	52	44.21	1.3714
3	902	872	856.66	0.2746	30	45.34	5.1882
4	1,123	1,085	1,083.89	0.0011	38	39.11	0.0318
5	910	849	877.28	0.9117	61	32.72	24.4436
6	856	822	826.44	0.0239	34	29.56	0.6669
7	787	760	759.80	0.0001	27	27.20	0.0015
8	812	804	786.29	0.3989	8	25.71	12.1987
9	712	701	692.16	0.1129	11	19.84	3.9383
10	647	631	632.20	0.0023	16	14.80	0.0968
11	554	547	543.52	0.0222	7	10.48	1.1526
12	495	491	487.19	0.0298	4	7.81	1.8604
13	354	351	349.21	0.0092	3	4.79	0.6686
14	237	231	234.37	0.0485	6	2.63	4.3281
>14.5	382	374	378.30	0.0487	8	3.70	1.1592
Totals	9,238	8,928	8,925.18	2.0364	310	312.82	57.1077

This should be compared to a table value of the chi-square distribution χ^2 with $15 - 2 = 13$ degrees of freedom. This table value for the $\alpha = 0.05$ level of significance is 22.36. Since the computed value $X^2 = 59.1441 > 22.36 = \chi^2$, the hypothesis that the model fits the data should be rejected.

Inspection of table 4 shows that the model seems to fit survival rates well. Summation of individual chi-square components for survival over all dbh classes is 2.0364, which is quite low. Rejection of the model is due to the mortality results, especially in the 5-inch and 8-inch dbh classes. The chi-square component for the 5-inch class is 24.4436, while the chi-square component for the 8-inch class is 12.1987. Chi-square components for mortality in other dbh classes is quite low. Inspection of mortality in the 5-inch class indicates that the rate is much higher than in the adjoining classes. The reason for this is not known, but it would appear difficult to fit the mortality trend through the 5-inch class in a manner consistent with results from other classes.

In general, mortality rates are quite low in these data, since they come from thinned stands. Except for Freese thinning study data, most plots were thinned from below at the beginning of the measurement interval, so that most suppressed trees where removed. The Freese study plots also had a history of thinning, but the measurement interval used did not occur immediately after thinning treatments. Only 310 of the 9,238 trees present at the first measurement died, leaving 8,928 at the second measurement. An overall annual mortality rate of between 0.7 and 0.8 percent would be indicated by compound interest formulas, although an exact computation is complicated by the fact that measurement intervals were not the same for all plots.

SUMMARY AND CONCLUSIONS

A logistic model for prediction of survival probabilities for individual shortleaf pine trees growing in even-aged natural stands was developed on the basis of data from remeasured plots located in eastern Oklahoma and western Arkansas. Although a chi-square test failed to accept the model, this was primarily due to results in only 2 of 15 dbh classes examined. Two of the independent variables used in the model, ratio of QMD to dbh and basal area per acre, are highly significant on the basis of the ratio between parameter estimates and associated standard errors. In all but the 5- and 8-inch classes, predictions from the model correspond to observed data reasonably well. Trials with models having a number of other combinations of independent variables failed to produce better survival estimates. Since this model is a better alternative than a constant mortality rate for all trees, it was selected for use in the ShortLeaf Pine Stand Simulator (SLPSS) (Huebschmann *et al.* 1998), an individual tree simulator for naturally occurring shortleaf pine stands.

ACKNOWLEDGMENTS

The following people reviewed this manuscript: Lawrence R. Gering and Robert F. Wittwer, Department of Forestry, Oklahoma State University, Stillwater, OK, USA.

LITERATURE CITED

Amateis, R.L.; Burkhart, H.E.; Walsh, T.A. 1989. Diameter increment and survival equations for loblolly pine trees growing in thinned and unthinned plantations on cutover, site-prepared lands. Southern Journal of Applied Forestry. 13(4): 170-174.

Bolton, R.K.; Meldahl, R.S. 1990. User's guide to a multipurpose forest projection system for southern forests. Bull. 604. Auburn University, Alabama: Alabama Agricultural Experiment Station. 15 p.

Brinkman, K.A. 1967. Stand volume equations for shortleaf pine in Missouri. Res. Note NC-24. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 4 p.

Daniels, R.F.; Burkhart, H.E. 1975. Simulation of individual tree growth and stand development in managed loblolly pine plantations. Publ. FWS-5-75. Virginia Polytechnical Institute and State University, Division of Forestry and Wildlife Research. 69 p.

Graney, D.L.; Burkhart, H.E. 1973. Polymorphic site index curves for shortleaf pine in the Ouachita mountains. Res. Pap. SO-85. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 12 p.

Hamilton, D.A. 1974. Event probabilities estimated by regression. Res. Pap. INT-152. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 18 p.

Hamilton, D.A.; Edwards, B.M. 1976. Modeling the probability of individual tree mortality. Res. Pap. INT-185. Ogden, UT: U.S. Department of Agriculture. Forest Service, Intermountain Forest Range Experiment Station. 22 p.

Hamilton, D.A.; Wendt, D.L.R. 1975. SCREEN: a computer program to identify predictors of dichotomous dependent variables. Gen. Tech. Rep. INT-22. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 20 p.

Hitch, K.L. 1994. A distance-independent individual tree basal area growth model for natural, even-aged stands of shortleaf pine in eastern Oklahoma and western Arkansas. Stillwater, OK: Oklahoma State University. 78 p. M.S. thesis.

Hosmer, D.W.; Lemeshow, S. 1980. A goodness-of-fit test for the multiple logistic regression model. Communications in Statistics. A10: 1043-1069.

Hosmer, D.W.; Lemeshow, S. 1989. Applied logistic regression. New York: John Wiley and Sons. 307 p.

Huebschmann, M.M.; Lynch, T.B.; Murphy, P.A. 1998. Shortleaf pine stand simulator, an even-aged natural shortleaf pine growth and yield model: user's manual. Res. Rep. P-967. Stillwater, OK: Oklahoma State University, Agricultural Experiment Station. 25 p.

Lynch, T.B.; Murphy, P.A. 1995. A compatible height prediction and projection system for individual trees in natural, even-aged shortleaf pine stands. Forest Science. 41(1): 194-209.

Lynch, T.B.; Murphy, P.A.; Lawson, E.R. 1991. Stand volume equations for managed natural even-aged shortleaf pine in eastern Oklahoma and western Arkansas. Res. Rep. P-921. Stillwater, OK: Oklahoma State University Agricultural Experiment Station. 12 p.

Miner, C.L.; Walters, N.R.; Belli, M.L. 1989. A technical guide to TWIGS for the North Central U.S. Gen. Tech. Rep. NC-125. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 105 p.

Murphy, P.A. 1982. Sawtimber growth and yield for natural even-aged stands of shortleaf pine in the West Gulf. Res. Pap. SO-181. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 13 p.

Murphy, P.A.; Beltz, R.C. 1981. Growth and yield of shortleaf pine in the West Gulf region. Res. Pap. SO-169. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 15 p.

Murphy, P.A.; Farrar, R.M., Jr. 1985. Growth and yield of uneven-aged shortleaf pine in the Interior Highlands. Res. Pap. SO-218. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 11 p.

Neter, J.; Wasserman, W.; Kutner, M.H. 1989. Applied linear regression models, 2d ed. Homewood, IL: Irwin. 667 p.

SAS Institute Inc. 1988. SAS/STAT™ user's guide, release 6.03 Ed. Cary, NC: SAS Institute Inc. 1028 p.

Schumacher, F.X.; Coile, T.S. 1960. Growth and yield of natural stands of the southern pines. Durham, NC: T.S. Coile, Inc. 115 p.

USDA Forest Service. 1929 (rev. 1976). Volume, yield and stand tables for second-growth southern pines. Misc. Publ. 50. Washington, DC: U.S. Department of Agriculture. 202 p.

Walker, S.H.; Duncan, D.B. 1967. Estimation of the probability of an event as a function of several independent variables. Biometrika. 54: 167-179.

Comparing the STEMS and AFIS Growth Models With Respect to the Uncertainty of Predictions

Ronald E. McRoberts, Margaret R. Holdaway, and Veronica C. Lessard

Abstract.—The uncertainty in 5-, 10-, and 20-year diameter growth predictions is estimated using Monte Carlo simulations for four Lake States tree species. Two sets of diameter growth models are used: recalibrations of the STEMS models using forest inventory and analysis data, and new growth models developed as a component of an annual forest inventory system for the North Central region of the United States. Particular attention is focused on the effects that uncertainty in the values of predictor variables has on the uncertainty of model predictions. The cumulative effects of uncertainty in model predictions for individual trees on the uncertainty of basal area predictions at the plot and regional levels are also investigated.

The North Central Research Station (NCRS) uses the STEMS (Belcher *et al.* 1982) diameter growth models as a component of its periodic inventory system to update the status of trees on Forest Inventory and Analysis (FIA) plots not measured in the current cycle. These models predict annual diameter growth for individual trees for pure or mixed and even- or uneven-aged stands for nearly all species in the North Central region of the United States; these models have also been recalibrated for other regions. NCRS is also developing new diameter growth models to be used as a component of an annual forest inventory system. The criterion for selection of predictor variables for these kinds of models is usually a measure of quality of fit of the model to calibration data. However, when non-negligible uncertainty is associated with the values of the predictor variables, then additional criteria ought to be considered. Uncertainty in a predictor variable occurs when large measurement errors are associated with values of the variable, as is frequently the case with ocular measurements, or when the values of the variable are estimates based on samples. When such predictor variables are included in models, the effects of their uncertainties may substantially increase the total uncertainty in model predictions. In statistics, the estimation of parameters under these conditions falls into the category of problems referred to as errors in variables (Fuller 1987).

The objectives of the study, of which this paper is a preliminary report, are threefold: (1) to estimate the total uncertainty in diameter growth model predictions; (2) to investigate the effects of including predictor variables with non-negligible uncertainty in growth models; and (3) to compare the uncertainty of predictions obtained from the STEMS models, recalibrated using Forest Inventory and Analysis (FIA) data, with the uncertainty of predictions obtained from the new models developed as a component of the annual forest inventory system.

METHODS

Uncertainty Estimation

Our approach to estimating the uncertainty in model predictions uses Monte Carlo simulations. The essence of the simulation process, explained in detail below, is to initialize plot and tree conditions using actual measurements from permanent FIA plots, add random variation where appropriate to mimic uncertainty, use the models to predict annual diameter growth, record estimates at fixed intervals, and repeat the process many times. As part of the process, plot-level estimates of basal area per acre are obtained by summing results over all trees on plots, and regional estimates of basal area and basal area growth are obtained by summing results over all plots. Because the regional basal area and basal area growth estimates are based on results from only 20 plots (see DATA section), they do not necessarily accurately represent true regional growth estimates. However, these estimates permit investigation of the effects on uncertainty when plot-level estimates are aggregated to produce estimates for larger areas. Finally, although mortality is an important component of growth, it is being addressed in other work, and no provision is made in this study for mortality during the prediction interval.

For this application, a Monte Carlo process is used to generate uncertainty for a variety of sources in two broad categories: first, calibration of the growth models, and second, initial conditions for trees and plots for which the model is used to predict growth. In the first category, uncertainty arises from two sources: (1) residual variation around estimated diameter growth curves; and (2)

Mathematical Statistician, Mathematical Statistician, and Research Forester, respectively, North Central Research Station, USDA Forest Service, 1992 Folwell Avenue, St. Paul, MN, USA.

uncertainty in the estimates of the growth model parameters. When uncertainty in the predictor variables is negligible and when the models are applied to initial conditions that are known with only negligible uncertainty, then these are the only two sources of variation that need be considered in estimating model prediction uncertainty. For this study, uncertainty for the latter source is excluded, because estimates of parameter covariances for nonlinear models are notoriously unreliable when obtained using analytical methods and because the alternative empirical methods require extensive, time-consuming simulations that have not been completed. When uncertainty in initial tree and plot conditions is non-negligible, then it must be propagated through the models and frequently results in substantially greater model prediction uncertainty. Thus, the Monte Carlo process is also used to generate uncertainty in four additional sources related to the uncertainty of the initial conditions of trees and plots: (3) diameter measurement error; (4) crown ratio observation error; (5) crown class observation error; and (6) variance in site index estimates. It should be noted that uncertainty in dbh measurements generates additional uncertainty in variables derived from dbh such as stand basal area and stand average diameter. In addition, when sampling is conducted for variable radius plots, dbh measurement error affects tree expansion factors and, hence, estimates of numbers of trees per acre.

Estimates of residual variation were obtained as byproducts of calibrating the models (Lessard 2000, Holdaway 2000). Residual variation is assumed to be normally distributed but heterogeneous with standard deviations related to predicted growth as follows:

$$E[\ln(\sigma)]=\beta_1+\beta_2\ln(\Delta d), \qquad [1]$$

where E(.) represents statistical expectation, Δd is annual diameter growth prediction, σ is the standard deviation of the residuals for predicted diameter growth classes of small widths, and the βs are parameters to be estimated.

Distributions representing the uncertainty in crown class, crown ratio, site index, and diameter measurement error were obtained from the literature. Nichols *et al.* (1991) reported that the repeatability of crown class observations by field crews in the same year is approximately 80 percent with the other 20 percent allocated uniformly to the two adjacent classes. McRoberts *et al.* (1994) reported that observations of crown ratio for the same tree by separate field crews ranged ± 0.3 from the median; they also provide a mathematical model for estimating diameter measurement error as a function of diameter. Finally, McRoberts (1996) reported that coefficients of variation for site index estimates, assumed to be normally distributed, may be as great as 0.15, depending on the number of trees used in calculating the estimate.

The Monte Carlo process for this application involves six steps: (1) mimic uncertainty in initial plot conditions by adding randomly generated variation to plot-level variables such as site index; (2) mimic uncertainty in initial tree conditions by adding randomly generated variation to tree-level variables such as crown ratio, crown class, and diameter; (3) use the models to predict annual diameter growth for each tree, mimic residual uncertainty in the predictions with randomly generated variation, and obtain predicted diameter at the beginning of the subsequent year as the sum of diameter at the beginning of the year, predicted annual diameter growth, and residual variation; (4) repeat step 3 to mimic growth of trees for 20 consecutive years; (5) record diameter predictions for trees, basal area per acre predictions for plots, and basal area and basal area growth predictions for the region at the 5-, 10-, and 20-year intervals; and (6) replicate steps 1-5 many times. In step 5, the basal area per acre estimate for each plot is obtained by multiplying the tree basal area estimate and the corresponding tree expansion factor for all trees and then summing these products for all trees on the plot. Relative estimates of basal area and basal area growth at the regional level are obtained by adding basal area per acre and basal area growth per acre, respectively, over all plots under the simplifying assumptions that each plot represents an area of 1 acre and that the plots represent a simple random sample of the population.

Distributions of the coefficients of variation ($CV=\sigma/\mu$) obtained from 1,000 replications of the simulation process serve as the basis for analyzing the uncertainty of model predictions. Mean values, standard deviations, and coefficients of variation for simulated dbh for individual trees stabilized by completion of 1,000 simulations (fig. 1). The results of the simulations are summarized as median coefficients of variation for diameter estimates of individual trees (table 1), median coefficients of variation for plot-level estimate of basal area (table 2), and regional estimates of basal area and basal area growth (table 3) at 5-, 10-, and 20-year intervals. For individual trees and plot estimates, the summaries are in terms of medians because of possible asymmetry in the distributions.

The uncertainty of model predictions is analyzed with respect to several factors and conditions. First, prediction uncertainty is obtained by conducting the simulations using all sources of variation and serves as a basis for comparing the recalibrated STEMS models and the new models. The contributions to model prediction uncertainty due to uncertainty in individual predictor variables is determined by including the variable when calibrating the model and then comparing the corresponding uncertainties of model predictions when the variable is both excluded and included as a source of uncertainty in the simulations. The results are used to assess the sensitivity of the uncertainty in model predictions to individual

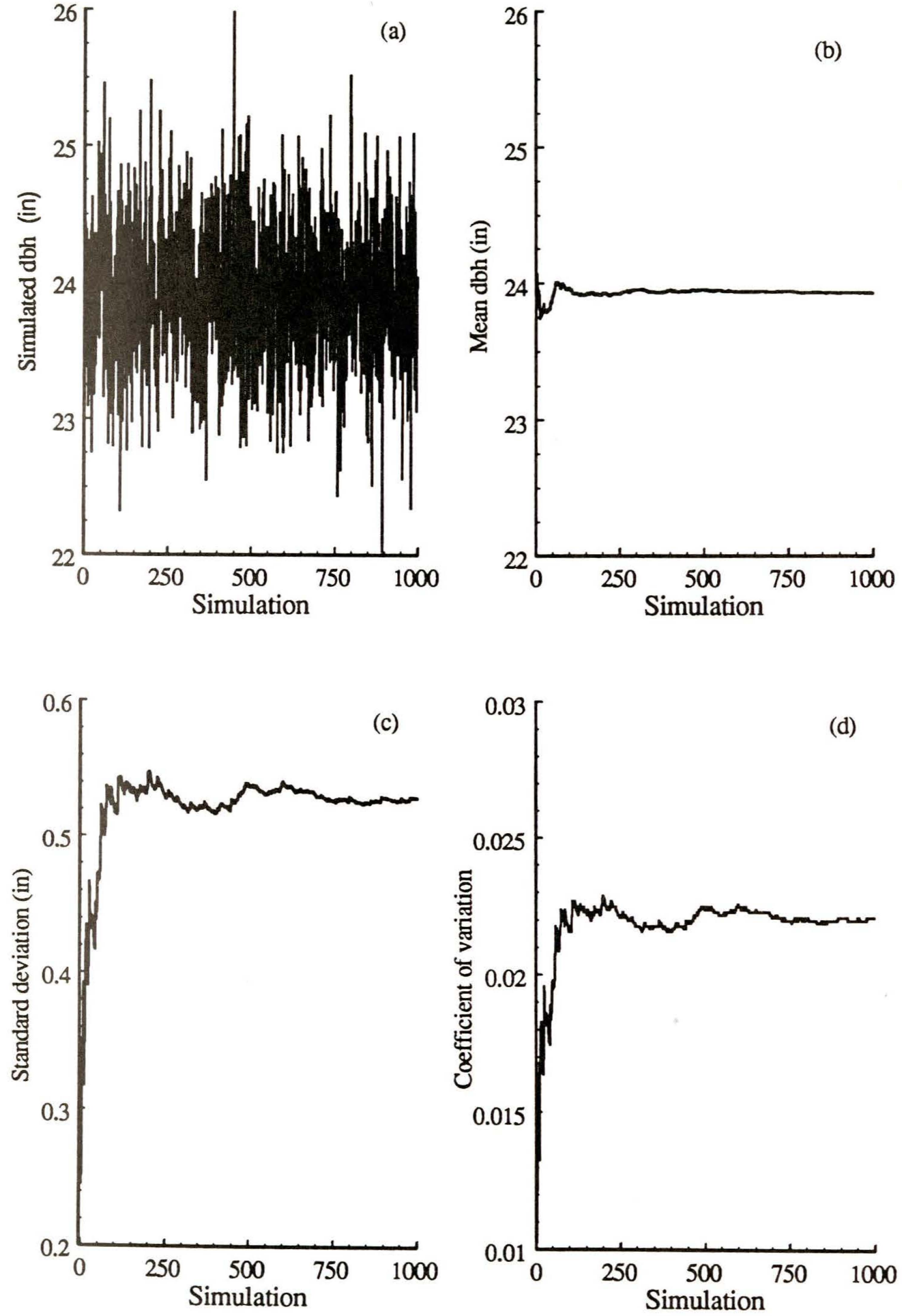


Figure 1.—*Simulation results for a sample tree: (a) simulated values of dbh after 20 years; (b) mean of simulated values of dbh after 20 years; (c) standard deviation of simulated values of dbh after 20 years; and (d) coefficient of variation of simulated values of dbh after 20 years.*

Table 1a.—*Median coefficients of variation for tree diameter estimates using STEMS-FIA*

Model calibration variables	Sources of uncertainty				Coefficient of variation[1]		
	Res[2]	**DBH**	**CR**	**SI**	**5-yr**	**10-yr**	**20-yr**
All[3]	x				0.096	0.107	0.121
All	x	x			0.140	0.146	0.160
All	x	x	x		0.156	0.171	0.195
All	x	x		x	0.140	0.149	0.163
All	x	x	x	x	0.156	0.166	0.196

[1] Coefficient of variation: CV= $\hat{\sigma}/\hat{\mu}$.

[2] Residual variability resulting from model calibration and applied using [1].

[3] DBH, CR, SI, AD, BA.

Table 1b.—*Median coefficients of variation for tree diameter estimates using AFIS*

Model calibration variables	Sources of uncertainty				Coefficient of variation[1]		
	Res[2]	**DBH**	**CC**	**CR**	**5-yr**	**10-yr**	**20-yr**
All[3]	x				0.094	0.117	0.138
All	x	x			0.161	0.179	0.198
All	x	x	x		0.168	0.185	0.204
All	x	x		x	0.225	0.235	0.294
All	x	x	x	x	0.214	0.258	0.314
All except CR	x	x	x		0.161	0.181	0.186
DBH only	x	x			0.139	0.143	0.138

[1] Coefficient of variation: CV= $\hat{\sigma}/\hat{\mu}$.

[2] Residual variability resulting from model calibration and applied using [1].

[3] DBH, CR, CC, BAL, BA, AD, PHY, NT.

Table 2a.—*Median coefficients of variation for plot basal area estimates using STEMS-FIA*[1]

Model calibration variables	Sources of uncertainty				Coefficient of variation		
	Res	DBH	CR	SI	5-yr	10-yr	20-yr
All	x				0.055	0.061	0.056
All	x	x			0.069	0.069	0.065
All	x	x	x		0.078	0.097	0.111
All	x	x		x	0.085	0.108	0.129
All	x	x	x	x	0.103	0.132	0.160

[1] See footnotes at the end of table 1a.

Table 2b.—*Median coefficients of variation for plot basal area estimates using AFIS*[1]

Model calibration variables	Sources of uncertainty				Coefficient of variation		
	Res	DBH	CC	CR	5-yr	10-yr	20-yr
All	x				0.051	0.061	0.064
All	x	x			0.071	0.075	0.079
All	x	x	x		0.061	0.075	0.074
All	x	x		x	0.085	0.120	0.147
All	x	x	x	x	0.082	0.112	0.155
All except CR	x	x	x		0.076	0.079	0.071
DBH only	x	x			0.080	0.088	0.096

[1] See footnotes at the end of table 1b.

Table 3a.—Coefficients of variation for regional basal area estimates using STEMS-FIA[1]

Model calibration variables	Sources of uncertainty				Coefficient of variation					
					Basal area growth			Basal area		
	Res	DBH	CR	SI	5-yr	10-yr	20-yr	5-yr	10-yr	20-yr
All	x				0.010	0.007	0.004	0.003	0.004	0.003
All	x	x			0.008	0.006	0.005	0.003	0.004	0.003
All	x	x	x		0.011	0.009	0.009	0.004	0.005	0.007
All	x	x		x	0.023	0.022	0.022	0.008	0.011	0.015
All	x	x	x	x	0.022	0.021	0.021	0.008	0.011	0.015

[1] See footnotes at the end of table 1a.

Table 3b.—*Coefficients of variation for regional basal area estimates using AFIS*[1]

Model calibration variables	Sources of uncertainty				Coefficient of variation					
					Basal area growth			Basal area		
	Res	DBH	CC	CR	5-yr	10-yr	20-yr	5-yr	10-yr	20-yr
All	x				0.010	0.006	0.004	0.003	0.003	0.003
All	x	x			0.010	0.008	0.005	0.004	0.005	0.004
All	x	x	x		0.008	0.005	0.004	0.004	0.004	0.003
All	x	x		x	0.013	0.013	0.013	0.005	0.007	0.010
All	x	x	x	x	0.014	0.013	0.014	0.005	0.007	0.010
All except CR	x	x	x		0.010	0.007	0.003	0.004	0.004	0.003
DBH only	x	x			0.005	0.004	0.003	0.004	0.003	0.003

[1] See footnotes at the end of table 1b.

sources of uncertainty. Third, the relative importance of a variable is evaluated by comparing the uncertainty of predictions for two conditions: (1) the variable is both included in the model calibration and included as a source of uncertainty in the simulations; and (2) the variable is excluded from the model calibration and, therefore, is excluded as a source of uncertainty in the simulations. If the uncertainty of predictions associated with (2) is less than with (1), then serious consideration ought to be given to excluding the variable from the model, even if its inclusion significantly increases the quality of fit of the model to the data. In these simulations, no consideration was given to correlations among the measurement errors or uncertainties for different sources.

Models

For more than a decade, the Forest Inventory and Analysis program at the North Central Research Station has used the STEMS diameter growth models (Belcher *et al.* 1982) to predict the current diameter of trees on plots not measured in the current year. Although the STEMS models are used in FIA applications, they were originally calibrated using data obtained from research plots. Holdaway (2000) documents some of the differences in these two sources of data. As a means of assessing the effects of applying the STEMS models to data that differ from those from which they were developed, we recalibrated the STEMS models for several Lake States species using FIA data (Lessard 2000) and designated the results as the STEMS-FIA models. Predictions with both STEMS and STEMS-FIA are obtained as products of two components, a potential growth component and a modifier component. The potential component, calibrated from observations of dominant and co-dominant trees only, uses current diameter at breast height (dbh), stand site index (SI), and crown ratio (CR) to predict the potential diameter growth of a tree. The modifier component, calibrated from trees of all crown classes, reduces growth from the potential using measures of competition based on stand basal area (BA), maximum observed basal area for the species (BAmax), and the ratio of dbh to average stand diameter (AD). Some of the STEMS predictor variables, notably crown class, crown ratio, and site index, have been demonstrated to have non-negligible uncertainty.

Advances in statistical estimation methodology since development of the STEMS models in the late 1970's and early 1980's have led to better modeling techniques and to greater understanding of the negative effects of uncertainty in predictor variables. Thus, as a part of our effort to develop annual forest inventory procedures, we are constructing new diameter growth models based on slightly different concepts and using more current statistical methodology (Holdaway 2000). These models are designated AFIS for their intended application in an annual forest inventory system. Predictions with the AFIS models are obtained as products of a regional median growth component expressed as a three-parameter Weibull-type function (Yang *et al.* 1978) of dbh and a modifier component expressed as the exponential of a linear combination of factors reflecting departures from regional median conditions for CR, BA, AD, crown class (CC), physiographic class (PHY), number of trees per acre (NT), and basal area in trees larger than the subject tree (BAL).

Data

The STEMS-FIA and AFIS models were both calibrated using FIA data obtained from the 1977 and 1990 periodic inventories in northeastern Minnesota for red pine (*Pinus resinosa* Ait.), balsam fir (*Abies balsamea* (L.) Mill.), quaking aspen (*Populus tremuloides Michx.*), and paper birch (*Betula papyrifera* Marsh.). The data used to initialize the simulations consist of plot- and tree-level observations obtained for FIA Unit 2 in northeastern Minnesota from the 1990 inventory. Because both the STEMS-FIA and AFIS models predict diameter growth for individual trees within the competitive environment of all trees growing on a plot, the predicted growth for an individual tree depends to some degree on the predicted growth of all trees on the plot. Thus, the data used to initialize the simulations were restricted to observations for plots consisting of only the four species for which the models had been calibrated. This data set consisted of observations for 441 trees growing on 20 plots.

RESULTS

Tree Diameter Estimates

When the models were calibrated using the full set of predictor variables, the uncertainty in initial plot and tree conditions substantially increased the uncertainty of model diameter predictions for both the STEMS-FIA and AFIS models (table 1a-b) (fig. 2). For example, the median coefficient of variation for 20-year AFIS predictions increased from 0.138 when only residual variability was considered to 0.314 when uncertainty from all sources was considered. At all time intervals, median values of coefficients of variation were less for the STEMS-FIA models than for the AFIS models when both models were calibrated with the full set of predictor variables and when all sources of uncertainty were used to estimate model prediction uncertainty. Although residual variability and dbh measurement error had the greatest individual effects on the uncertainty of model predictions for both models, neither of these sources can be eliminated; residual variability is unavoidable, and dbh is fundamental to the underlying model. Of the remaining sources of uncertainty, crown ratio had the single greatest detrimental effect for both models. As a test of the overall

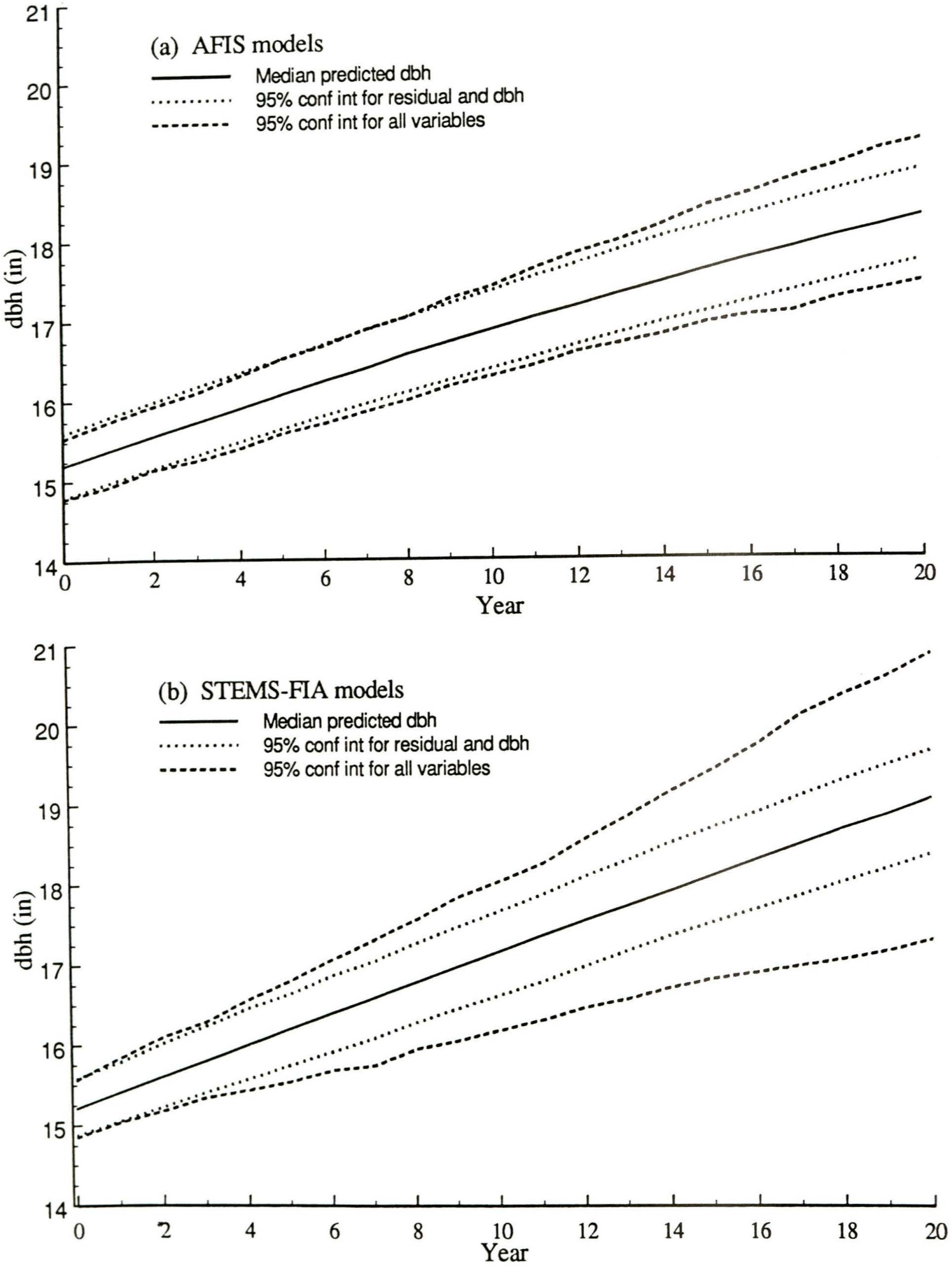


Figure 2.—*Ninety-five percent confidence intervals for predicted dbh of a sample tree; models calibrated with all variables (see footnotes on table 1a-b); confidence interval based on uncertainty from indicated sources: (a) AFIS; (b) STEMS-FIA.*

effect of this variable, the AFIS models were calibrated without using crown ratio as a predictor, a new relationship between predicted growth and residual variability as per [1] was estimated, and the simulations were repeated. The result of eliminating crown ratio as a predictor variable and as a source of uncertainty in initial conditions was a decrease in the uncertainty of predictions (table 1b). Without consideration of bias, this result suggests that although crown ratio was a significant predictor variable when fitting the model to the calibration data, the overall effect of the variable was an increase in the model prediction uncertainty. Similarly, model prediction uncertainty was reduced even more when all predictor variables except dbh were deleted from the model (table 1b).

Plot-level Basal Area Per Acre Estimates

At the plot level, the uncertainty in predictor variables also had a negative effect on the uncertainty of predictions for both models when they were calibrated with the full set of predictor variables (table 2a-b). However, in contrast to the tree-level results, uncertainty in plot-level estimates was somewhat less for the AFIS models. This result is attributed to the negative effects of uncertainty in site index, a plot-level predictor variable used in the STEMS-FIA models but not in the AFIS models. As with the diameter predictions, prediction uncertainty for the AFIS models was less when dbh was the only predictor variable than when all predictor variables were included in the model.

Regional Basal Area and Basal Area Growth Estimates

Uncertainty in predictor variables had a negative effect on the uncertainty of regional estimates of both basal area and basal area growth, but the effect was not nearly as severe as for tree- and plot-level estimates (table 3a-b). At the regional level, the AFIS models produced estimates with less uncertainty than did the STEMS-FIA models, a result that is again attributed to the effects of uncertainty in the plot-level predictor variable, site index, in the STEMS-FIA models. As with the tree- and plot-level results, removal of CR from the set of predictor variables reduced the uncertainty of AFIS predictions; the greatest reduction was achieved when all predictor variables except dbh were removed from the model.

CONCLUSIONS

Six immediate conclusions appear evident: (1) uncertainty in initial plot- and tree-level conditions has a substantial, negative effect on the uncertainty of model predictions; (2) serious consideration and additional analyses are needed to determine if predictor variables with large uncertainties should be included in models; (3) although the uncertainty in diameter growth predictions for individual trees was relatively large, the effects of propagating this uncertainty to plot-level estimates of basal area per acre growth and to regional estimates of basal area were not severe; (4) without considering bias effects, eliminating all but the few most crucial predictor variables often produced the best results at the regional level; (5) the uncertainty of STEMS-FIA predictions at plot- and region-level were more sensitive to uncertainty in the plot-level predictor variable site index than to uncertainty in tree-level predictor variables; and (6) the AFIS models were as good or better than the STEMS-FIA models with respect to the uncertainty of plot and regional predictions.

Several broad conclusions also emerge. First, even when the only the source of uncertainty considered is residual variability, coefficients of variation were on the order of 0.10 or greater for tree diameter predictions, suggesting that it may be extremely difficult to develop precise individual tree diameter growth models when the calibration data are obtained from trees representing a broad geographic region. In addition, if uncertainty in parameter estimates had been included in the analyses, these coefficients of variation would have been even larger. Second, despite the uncertainty in diameter predictions, coefficients of variation on the order of 0.01 or less for regional basal area estimates suggest that reasonably precise estimates may be obtained at this level. Although these results will deteriorate when parameter covariances are included, this result is still encouraging. Finally, the conclusions suggest that for broad regional applications, predictions from simpler models with fewer predictor variables that capture basic growth relationships may be less uncertain than those from more complex models with many predictor variables that attempt to explain a large proportion of variation.

ACKNOWLEDGMENTS

The following people reviewed this manuscript: Gary Brand and Mark Hansen, USDA Forest Service, North Central Research Station, St. Paul, MN, USA, and H. Todd Mowrer, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA.

LITERATURE CITED

Belcher, D.W.; Holdaway, M.R.; Brand, G.J. 1982. A description of STEMS - the stand and tree evaluation and modeling system. Gen. Tech. Rep. NC-79. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 18 p.

Fuller, W.A. 1987. Measurement error models. New York, NY: John Wiley and Sons. 440 p.

Holdaway, M.R. 2000. A FIA tree growth model for updating annual forest inventories in Minnesota. In: Hansen, M.; Burk, T., eds. Integrating tools for natural resources inventories in the 21st century; 1998 August 16-20; Boise, ID. Gen. Tech. Rep. NC-212. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 507-514.

Lessard, V.C. 2000. Calibration of the STEMS diameter growth model on FIA data. In: Hansen, M.; Burk, T., eds. Integrating tools for natural resources inventories in the 21st century; 1998 August 16-20; Boise, ID. Gen. Tech. Rep. NC-212. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 525-532.

McRoberts, R.E.; Hahn, J.T.; Hefty, G.J.; Van Cleve, J.R. 1994. Variation in forest inventory field measurements. Canadian Journal of Forest Research. 24: 1766-1770.

McRoberts, R.E. 1996. Estimating variation in field crew estimates of site index. Canadian Journal of Forest Research. 26: 560-565.

Nichols, N.S.; Gregoire, T.G.; Zedaker, S.M. 1991. The reliability of tree crown position classification. Canadian Journal of Forest Research. 21: 698-701.

Yang, R.C.; Kozak, A.; Smith, J.H.G. 1978. The potential of Weibull-type functions as flexible growth curves. Canadian Journal of Forest Research. 8: 423-431.

Utilizing Inventory Information to Calibrate a Landscape Simulation Model

**Stephen R. Shifley, Frank R Thompson III, David R. Larsen,
David J. Mladenoff, and Eric J. Gustafson**

Abstract.—LANDIS is a spatially explicit model that uses mapped landscape conditions as a starting point and projects the patterns in forest vegetation that will result from alternative harvest practices, alternative fire regimes, and wind events. LANDIS was originally developed for Lake States forests, but it is capable of handling the input, output, bookkeeping, and mapping that occur during landscape simulations for virtually any forest region. We recently calibrated LANDIS for the forest conditions in the Missouri Ozarks, and we based that calibration on a combination of traditional forest inventory data, silvics information, and expert opinion. To ensure realistic model performance, we used inventory data to test species dynamics of the model and establish initial landscape conditions. Landscape simulation examples from the Missouri Ozarks illustrate the methodology by comparing results from even-aged management, uneven-aged management, and no-harvest scenarios.

In the past decade, forest management and planning has expanded to include a wide range of ecosystem values and attributes other than timber. This trend is particularly prevalent on public lands where characteristics such as nongame wildlife species, threatened and endangered plants and animals, water quality, biodiversity, and landscape diversity must be explicitly addressed. Issues of scale present some of the greatest difficulties in managing forest ecosystems for an array of attributes. Silvicultural operations for timber production are implemented on stands that typically range from 2 to 10 ha in size in the midwestern United States. Other attributes such as water quality, wildlife habitat quality, and biodiversity must be addressed at larger scales—often across hundreds or thousands of hectares. Characterization of these attributes often requires information on the juxtaposition of vegetation age classes across a landscape.

Several tools and procedures to facilitate planning and management across forest landscapes already exist. Products such as UTOOLS (Mcgaughey and Ager 1996, Mcgaughey 1998), CRBSUM (Keane *et al.* 1996), LANDIS (He *et al.* 1996, Mladenoff *et al.* 1996), and many others (Mowrer 1997) all have demonstrated the capacity to support aspects of landscape-scale forest management in other regions. Until recently, none of these tools has been applied in the Midwest.

In 1994, we began developing tools to predict response of central hardwood forests to disturbance. The ability to predict responses to both natural and anthropogenic disturbances is essential in managing forest ecosystems here. Our intent was to develop a system to predict forest change at sufficiently large spatial scales (thousands of hectares) and long time frames (at least a century) to support simultaneous analysis of an array of forest attributes (e.g., timber, wildlife, aesthetics, and economics). Although there is information about each of these attributes individually, how they interact under different disturbance regimes has been hard to predict because the relevant spatial and temporal scales differ among the attributes of interest.

Our approach was predicated on the following assumptions:

- Central hardwood forests are constantly responding to (or recovering from) disturbance by fire, wind, and tree harvest.
- At a coarse scale, patterns of forest growth and succession are predictable.
- Landscapes can be divided into ecologically similar units that improve the predictability of vegetation response to disturbance.
- We can infer things about other ecosystem components such as wildlife habitat quality, forest products, landscape diversity, and aesthetics from knowledge of vegetation composition and structure across a landscape.

Our challenge was to find a means to predict forest structure and composition in a spatially explicit model capable of tracking the location of disturbance events, linking disturbances to the specific forest vegetation communities affected, and predicting how the forest vegetation and other attributes will change over time.

Research Forester and Project Leader, USDA Forest Service, North Central Research Station, Columbia, MO, USA, Associate Professor, School of Natural Resources, University of Missouri, Columbia, MO, USA; Associate Professor, Department of Forest Ecology and Management, University of Wisconsin, Madison, WI, USA; and Research Forester, USDA Forest Service, North Central Research Station, Rhinelander, WI, USA, respectively.

This required creating a dynamic map of predicted forest conditions through time.

Conceptually, this problem is easy to grasp; forest planners think about this every day. However, creating a quantitative framework to manipulate a mapped landscape requires a tremendous amount of detailed bookkeeping and data manipulation. Rather than build a new model, we used LANDIS, an existing landscape simulation model for the Lake States (Mladenoff *et al.* 1996, He *et al.* 1996). LANDIS operates on a map (raster) of the forest landscape and effectively deals with many of the computational complexities associated with tracking forest conditions through time on a mapped landscape. It accommodates up to 256 ecological land units and can be calibrated so that patterns of vegetation change are specific to each ecological land unit. Model resolution can be varied by changing the map pixel size from less than 100 m^2 to a square kilometer or more. LANDIS's algorithms to model fire and wind disturbance, coupled with the newly developed routines to model timber harvest (Gustafson *et al.* in prep.), provide a general framework to predict forest response to disturbance. Compared to traditional forest growth and yield models, the resolution of LANDIS for a given site on the landscape is low. It tracks only the presence or absence of tree species by age class. It does not estimate the density or volume of overstory vegetation; that must be inferred from the age structure and disturbance history at a given site. But for landscapes consisting of millions of mapped sites, the level of resolution is appropriate for many forest planning tasks, and greater detail can quickly lead to intractable computing and data manipulation problems.

The major barrier to applying LANDIS in the central hardwood region was the need to calibrate the vegetation dynamics and disturbance processes for local conditions. In this paper we describe the procedures used to recalibrate and apply LANDIS in the Missouri Ozarks. The process required a combination of existing inventory data and professional judgment. An example illustrates the application of the model to examine the results of alternative harvest strategies on a forest landscape in Missouri.

METHODS

Model calibration included three major phases: (1) calibrating species dynamics by ecological land type, (2) setting appropriate rates of fire disturbance, and (3) setting appropriate rates of wind disturbance. We focused on upland forest sites in the Missouri counties of Carter, Dent, Reynolds, and Shannon where a large quantity of high-quality multi-resource data was already available. Previous and ongoing research there provided a large body of multi-resource data and extensive maps of ecological land types and current forest cover.

Data

Inventory data to support calibration of species dynamics by ecological land type came from three sources. The first was the Missouri Ozark Forest Ecosystem Project (MOFEP), a landscape-scale field experiment investigating the effect of harvest methods on a host of ecosystem characteristics (Brookshire and Hauser 1993, Brookshire and Shifley 1997) (fig. 1). This inventory included 648 0.2-ha circular plots where species, diameter, and other characteristics were measured for trees ≥ 11 cm dbh. This inventory was conducted in 1991-1993, prior to any treatments associated with the MOFEP experiment. The forest is predominantly in the 60- to 80-year age class and is unique in having received virtually no fire or harvest disturbance in the preceding 40 years. The second source of data was the Sinkin Experimental Forest, located on the Mark Twain National Forest in southeast Missouri (fig. 1). This 1,600-ha tract also was largely undisturbed in the previous 40 years, and the forest overstory is also in the 60- to 80-year age class. The inventory included 71 0.1-ha circular plots that sampled trees ≥ 10 cm in areas of the forest that had been excluded from silvicultural experiments. The third and final inventory sampled trees ≥ 10 cm on 60 0.1-ha inventory plots split between two remnant old-growth forests: Big Spring in Carter County and Roaring River in Barry County (fig. 1). Both of these areas have been preserved from harvest activity and are considered excellent examples of undisturbed old-forest. Dominant canopy trees range from 100 to well over 200 years old on these old-growth sites, and the canopy is punctuated by tree fall gaps that have resulted in a multi-aged forest (Shifley 1994; Shifley *et al.* 1995, 1997). Before the 1940's, all study sites were subject to the periodic wildfires (usually ground fires of anthropogenic origin) and open-range livestock grazing that were practiced then throughout the Ozarks. Since that time, all study sites have been free from major anthropogenic disturbances.

Data on recent forest fire patterns in the study region came from electronic wildfire records maintained by the Mark Twain National Forest and the Missouri Department of Conservation (Westin 1992). Historical fire frequencies were obtained from Guyette (1996) and Guyette and Dey (1997). Data on wind disturbance in the Missouri Ozarks came from 96 km of line transects in the Missouri Ozarks sampled by Alan Rebertus in 1995-1996 (personal communication).

Analysis

Calibration

The 20 ecological land types (ELTs) (Miller 1981) represented in the inventory data were combined to create a reduced set of seven principal ecological land types that

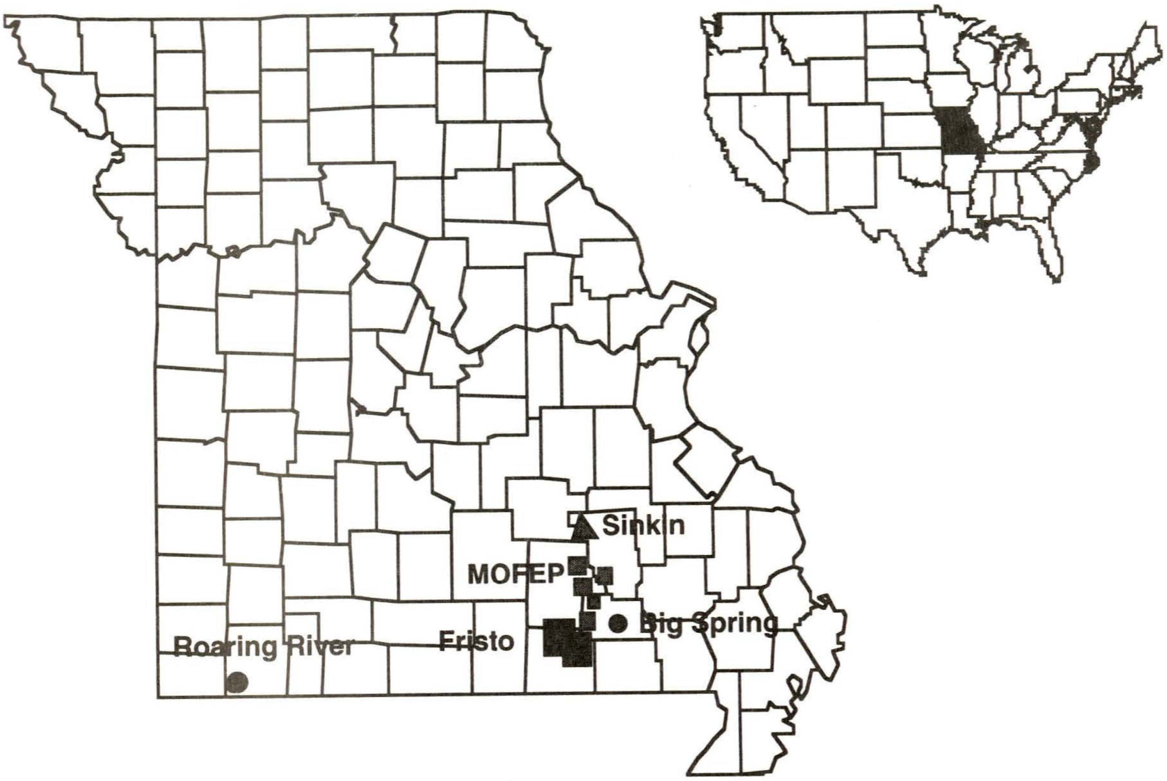


Figure 1.—*Location of study sites in southern Missouri used to calibrate and implement the model.*

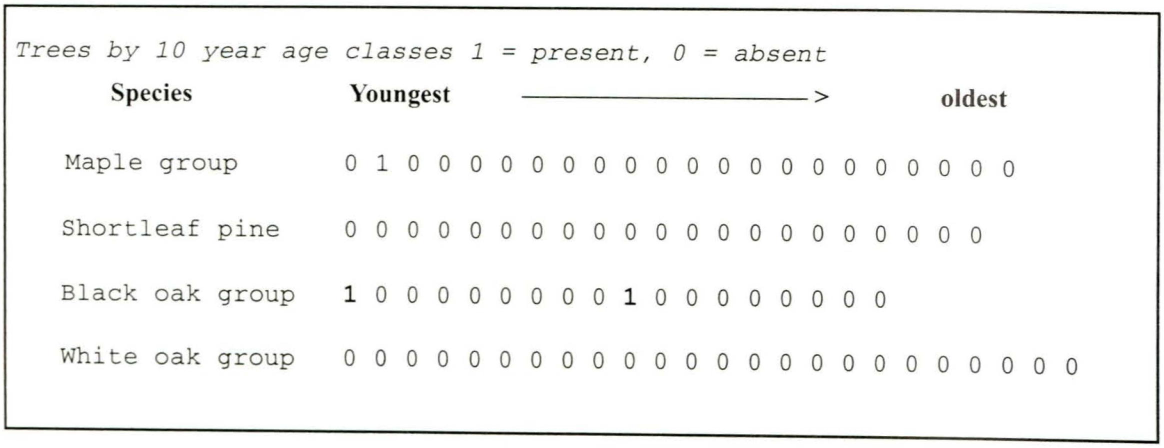
were used in LANDIS (table 1). Groupings were based on frequency of ELT occurrence and similarity of associated site conditions. This reduced set of seven ELTs was used in subsequent simulations. Woody vegetation data were summarized by plot and ecological land type. These data were further summarized to tally species presence/absence probabilities by age class in a format that corresponded with LANDIS's internal representation of trees on a forest site (fig. 2). The combined data for the MOFEP, Sinkin, and old-growth sites were used to develop a set of provisional species presence/absence values (i.e., target percentages) for undisturbed, mature forests. These targets served as a first approximation to the expected equilibrium species composition in a lightly disturbed forest on a given ELT. These targets were further refined by three local ecologists (Sybill Amelon, Mark Twain National Forest, Houston, Missouri; Alan Rebertus, University of Missouri, Columbia, Missouri; Tim Nigh, Missouri Department of Conservation, Columbia, Missouri) who estimated expected long-term (i.e., over a century) shifts in species composition in the absence of disturbance by wind, fire, or harvest.

We then calibrated LANDIS for the four principal overstory species groups in the study area: white oaks, red/black oaks, shortleaf pine, and maple. Life history characteristics for each species (e.g., shade tolerance, fire susceptibility, sprouting capacity, longevity) were determined from published silvical guides. Species reproduction probabilities in LANDIS were then established for each ELT. Initial estimated reproduction probabilities were iteratively adjusted until, for an initial landscape with (a) all species groups present in equal proportions, (b) all sites randomly populated with one of the four species groups, and (c) all trees in the youngest (10-year) age class, the projected species composition by ELT over time moved to within 10 percent of the target proportions for that ELT.

Based on fire data between 1970 and 1995, we computed a mean fire-free interval of 300 years (i.e., the mean time between repeat fires at the same location) for current fire suppression practices. Minimum and maximum fire sizes were set at 0.1 ha and 41 ha, respectively. Fire severity was set low to simulate the ground fires that commonly occur in the region. Simulated fires will kill trees in the smallest age classes with greatest frequency, and maple is more susceptible to fire damage than either the oak or shortleaf pine species groups. Major stand-replacing wind disturbances were simulated with an 800-year mean return interval, a minimum event size of 0.1 ha, and a maximum size of 20 ha.

Table 1.—*Major ecological land unit groupings used for landscape simulations in the Missouri Ozarks*

Composite ecological land units used for model calibration and simulation	Proportion of studysites	Included ecological land types from Miller (1981)	Proportion of study sites
	Percent		*Percent*
Dry chert forest on south and west slopes	34	17 Dry chert forest, south and west aspects	34
Dry-mesic northeast slopes	29	18 Dry –mesic chert forest, north and east aspects	29
Ridge tops and upland flats	27	10 Xeric chert forest, ridge top	<1
		11 Dry chert forest, ridge top	5
		14 Xeric chert forest, flat	1
		15 Dry chert forest, flat	20
Upland drainage	6	4 Gravel wash, upland waterway	<1
		5 Dry bottomland forest, upland waterway	2
		6 Dry-mesic bottomland forest, upland waterway	4
Mesic floodplain or low terrace	2	1 Wet-mesic bottomland forest, low floodplain	1
		2 Calcareous wet forest floodplain or low terrace	<1
		3 Mesic bottomland forest, floodplain or low terrace	1
		7 Mesic forest, toe slope	<1
		35 Mesic forest, sinkhole	<1
		36 Acid seep forest, sinkhole	<1
Side slope on limestone	1	20 Dry-mesic limestone forest, side slope	<1
		22 Xeric limestone forest, side slope	<1
		23 Dry limestone forest, side slope	1
Glade	<1	19 Glade savanna, side slope	<1
		21 Dolomite or limestone glade, side slope	<1



```
Trees by 10 year age classes 1 = present, 0 = absent
      Species          Youngest     ——————————————>        oldest

   Maple group         0 1 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

   Shortleaf pine      0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0

   Black oak group     1 0 0 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0

   White oak group     0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0
```

Figure 2.—*Numerical representation of trees on a site (i.e., 0.9 ha raster) within LANDIS. For a given 10-year age class a value of "1" indicates the presence of one or more trees of the indicated species. A value of "0" indicates absence of the species in the age class. During a decade where a site is undisturbed, trees (i.e., "1"s) will simply move one space to the right in the age class matrix. If the trees in an age class are killed by wind, harvest, or fire, the "1" in that age class is replaced by a "0." Differences in the number of age classes for each species reflect differences in species longevity.*

Initial Conditions

In addition to the model parameterization procedures outlined above, application of LANDIS requires an initial raster map of ecological land types. The raster elements (i.e., "sites" in the terminology associated with LANDIS documentation) can be scaled by the user to accommodate different model resolutions, but for our applications they were 30 m square or 0.09 ha. To simulate harvest, additional raster maps showing the location of stands and management areas were required. Management areas designate groups of stands that, over time, will receive the same harvest regime. For these simulations, the entire landscape was treated as a single management area. For more complicated simulations, multiple management included different harvest activities. A given stand must be wholly contained within a single ELT and a single management area.

There are few areas where stand boundaries and ecological land units have been mapped and vegetation conditions have been inventoried. Two such mapped landscapes in Missouri are the 200,000 ha Fristo unit of the Mark Twain National Forest and the 3,800 ha in the Missouri Ozark Forest Ecosystem Project. To facilitate display of the simulated results, we confined our examples to the forest landscape comprised of the 842 contiguous ha in MOFEP units 7 and 8 (Brookshire *et al.* 1997). The initial vegetation conditions (i.e., species and age class) were summarized by ecological land type from the 141 forest inventory plots located on those units. For the first year of simulation, sites (i.e., the individual 0.9 ha raster units) within a given ecological land type were randomly populated with species in the same proportion they were observed in the initial inventory data.

Disturbance Regimes

We simulated three forest management regimes: intensive even-aged management, uneven-aged management, and no timber harvest (table 2). We simulated each regime for 100 years and compared the resulting landscape characteristics.

RESULTS

Differences in the age structure that result from the different management practices are evident in maps of age class over time (fig. 3). After 100 years there are obvious differences in the area of early-successional (0-29 years) and late-successional forest (> 120 years) and their spatial distribution across our modeled landscape. Although harvest patterns (fig. 3) are responsible for most age-class differences among the three management treatments, the effects of simulated fires are also visible. For the no-harvest management alternative, all sites < 180 years old are the result of simulated fire and wind events. The pattern of cumulative fire and wind events for the no-harvest alternative (fig. 4) matches the pattern of sites that were regenerated during the simulation. The effects of fire are also evident in the relatively large patches of young forest in the uneven-aged management alternative at year 100. Although less obvious in the even-aged management alternative, age class variation within stand boundaries did result from fire events. Effects of large-scale wind damage (≥ 0.09 ha in extent) are far less a factor in shaping landscape age structure than are the effects of fire.

Table 2.—*Simulated disturbance regimes applied across the 842-ha landscape comprised of MOFEP units 7 and 8*

Harvest regime	**Harvest method**	**Area harvested**	**Harvest ranking algorithm**	**Mean interval between fires**	**Mean fire size**	**Min fire size**	**Max fire size**	**Mean interval between wind**	**Mean wind size**	**Min wind size**	**Max wind size**
		%/decade		*Years*	*ha*	*ha*	*ha*	*Years*	*ha*	*ha*	*ha*
Intensive even-aged management with fire suppression	Clearcut	10	Oldest stands first; don't harvest adjacent stands in same decade	300	8	0.1	607	800	1	0.1	20
Uneven-aged management with fire suppression	Group selection, mean group size 0.2 ha	5	Harvest oldest stands first	300	8	0.1	607	800	1	0.1	20
No harvest with fire suppression	None	0	N/A	300	8	0.1	607	800	1	0.1	20

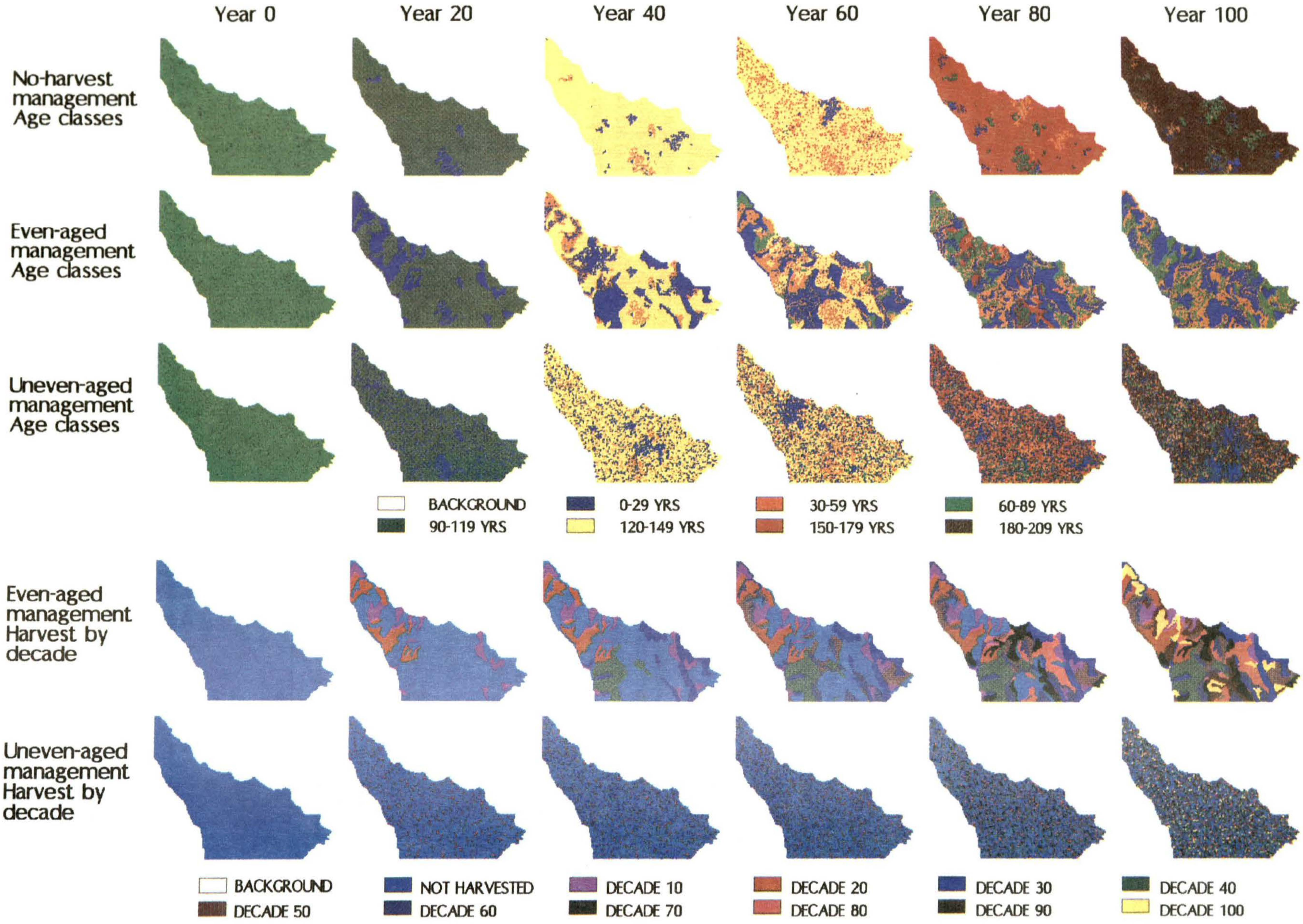

Year 0
Year 20
Year 40
Year 60
Year 80
Year 100
No-harvest management Age classes
Even-aged management Age classes
Uneven-aged management Age classes
BACKGROUND
0-29 YRS
30-59 YRS
60-89 YRS
90-119 YRS
120-149 YRS
150-179 YRS
180-209 YRS
Even-aged management Harvest by decade
Uneven-aged management Harvest by decade
BACKGROUND
NOT HARVESTED
DECADE 10
DECADE 20
DECADE 30
DECADE 40
DECADE 50
DECADE 60
DECADE 70
DECADE 80
DECADE 90
DECADE 100

Figure 3.—*Change in landscape age structure over 100 years of simulation comparing even-aged, uneven-aged, and no-harvest alternatives. Harvested stands and group openings are shown for the even-aged and uneven-aged harvest alternatives, respectively.*

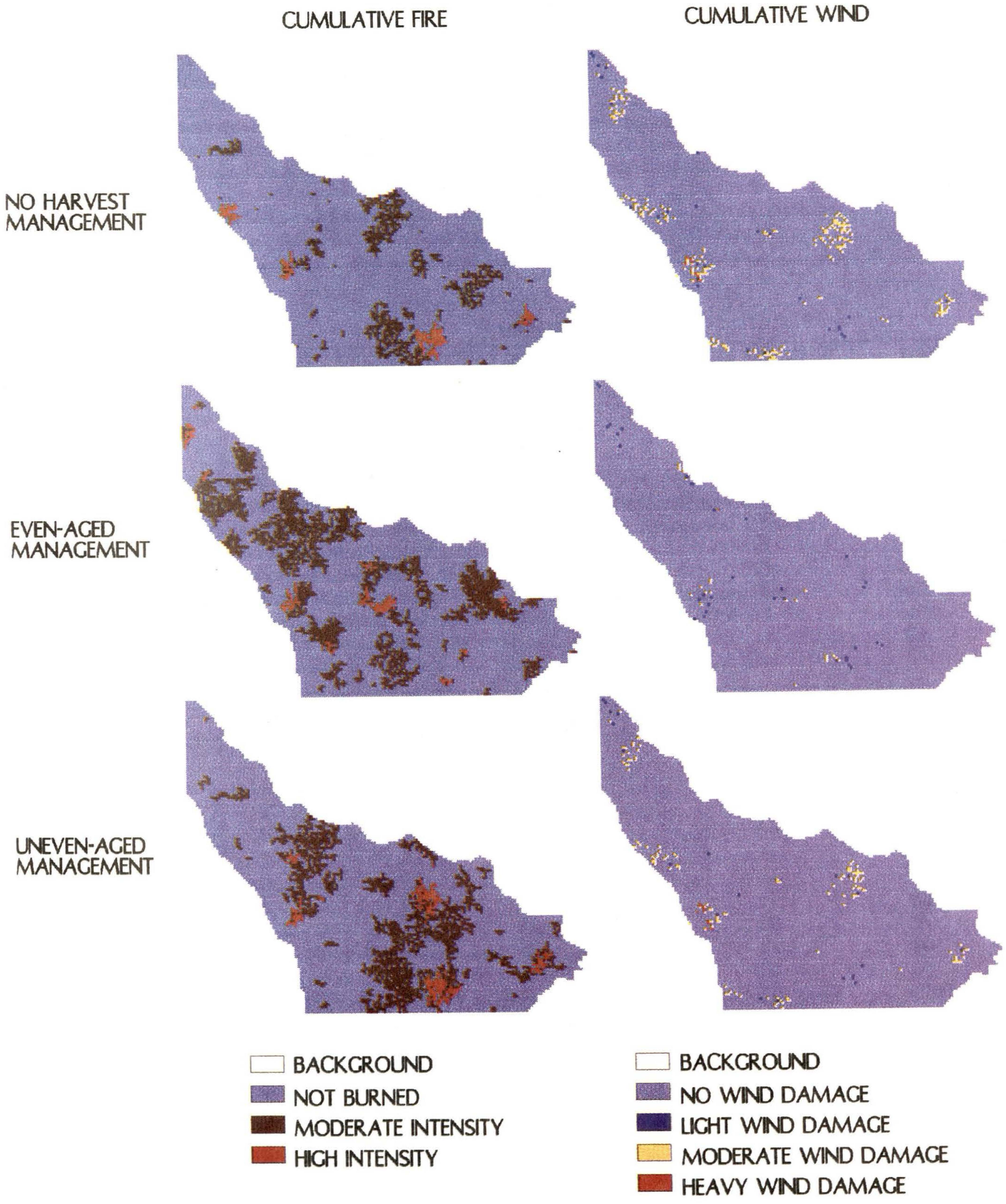

CUMULATIVE FIRE
CUMULATIVE WIND
NO HARVEST MANAGEMENT
EVEN-AGED MANAGEMENT
UNEVEN-AGED MANAGEMENT
☐ BACKGROUND
▨ NOT BURNED
■ MODERATE INTENSITY
■ HIGH INTENSITY
☐ BACKGROUND
▨ NO WIND DAMAGE
■ LIGHT WIND DAMAGE
■ MODERATE WIND DAMAGE
■ HEAVY WIND DAMAGE

Figure 4.—*Cumulative fire disturbance and cumulative wind disturbance over 100 years for each of the simulated alternatives. Location of fire and wind events varies among repeated runs of the same landscape unless the same random number sequence is repeated. Harvest patterns can affect simulated fires by altering the proportion of species and size classes most susceptible to fire damage.*

Mapped images are useful for displaying change through time and spatial diversity of landscape characteristics. Other maps produced from the simulations included species presence/absence and species presence/absence by age class. These values were further combined across stands to estimate forest type and size class (seedling, sapling, pole, and sawlog) combinations. The simulated landscape conditions at each point in time are stored as one or more raster maps of forest species and age characteristics for each 0.09-ha site. Further analysis using GIS software provided additional summaries of landscape condition by species and size class (tables 3 and 4).

The proportion of sites with shortleaf pine increased under all management alternatives, but the increase was most dramatic under the even-aged and uneven-aged

Table 3.—*Proportion of sites with each species present under the three simulated management alternatives. At year 0 each 30- by 30-m site contained only one species. In subsequent years sites often contained more than one species, and row totals for a single year may exceed 100 percent.*

Year	White oak group	Black oak group	Shortleaf pine	Maple group
		Percent		
		NO-HARVEST		
0	33	56	10	1
10	33	56	10	1
20	36	55	12	2
30	36	54	13	3
40	38	53	14	3
50	40	51	16	4
60	40	51	16	5
70	40	51	17	5
80	41	51	17	6
90	41	50	18	7
100	41	50	19	8
		EVEN-AGED		
0	33	56	10	1
10	36	59	13	1
20	38	57	14	2
30	40	51	17	2
40	41	48	19	2
50	47	46	25	2
60	51	45	30	1
70	55	44	36	1
80	59	42	41	1
90	60	42	47	0
100	62	43	51	0
		UNVEN-AGED		
0	33	56	10	1
10	37	58	14	1
20	41	59	19	2
30	45	60	23	2
40	49	60	28	2
50	53	59	33	2
60	56	61	37	3
70	59	64	41	3
80	61	65	44	3
90	62	64	48	3
100	63	64	51	3

Table 4.—*Area (ha) by size class for 100-year simulation of three management alternatives*

Year	No harvest			Even-aged			Uneven-aged		
	Seedling-sapling	Pole	Sawlog	Seedling-sapling	Pole	Sawlog	Seedling-sapling	Pole	Sawlog
0	0	0	842	0	0	842	0	0	842
10	0	0	842	87	0	755	66	0	777
20	26	0	816	199	0	644	147	0	696
30	36	0	807	247	65	530	155	51	636
40	28	25	789	286	122	434	159	114	569
50	38	32	772	300	203	339	187	154	501
60	22	49	771	311	229	303	168	174	499
70	11	42	789	297	261	285	146	188	508
80	18	35	789	310	265	267	158	184	501
90	27	27	789	338	268	237	182	166	494
100	28	19	795	332	274	237	188	156	498

management alternatives (table 3). The proportion of sites with white oak species increased relative to black oak species under all management regimes. Distribution of size classes at year 100 differed substantially among the three management alternatives. In the even-aged management alternative, the relative proportion of sites was evenly split among the seedling-sampling size class (0-29 years old), the pole size class (30-59 years old), and the sawlog size class (> 60 years old) (table 4). For the uneven-aged management alternative, 60 percent of the sites were in the sawlog size class, and the pole and seedling-sapling size classes each had approximately 20 percent of the area. Through the action of fire and wind disturbance, the no-harvest alternative consistently maintained 1 to 5 percent of sites in the pole and seedling-sapling size classes. Mean patch size by size class varied over the 100-year simulation period (table 5). In general, the even-aged management regime produced the largest patches in the seedling-sapling and pole size classes. The no-harvest management regime produced the largest patches of forest in the sawlog size class.

DISCUSSION

The amount of data and information required to calibrate and operate LANDIS in a new region is substantial. Calibration requirements include information about:

- wildfire size, frequency, and severity
- wind disturbance size, frequency, and severity
- species life history characteristics including
    - shade tolerance
    - fire tolerance
    - sprouting capacity
    - seed dispersal distance
    - age of reproductive maturity
    - longevity

Table 5.—*Mean patch size (ha) for 100-year simulation of three management alternatives*

Year	No harvest			Even-aged			Uneven-aged		
	Seedling-sapling	Pole	Sawlog	Seedling-sapling	Pole	Sawlog	Seedling-sapling	Pole	Sawlog
0	0	0	842	0	0	842	0	0	842
10	0	0	842	7	0	377	0.2	0	777
20	4	0	102	12	0	64	0.3	0	46
30	3	0	90	5	3	20	0.3	0.2	32
40	1	4	72	4	3	13	0.3	0.2	15
50	1	2	41	4	3	9	0.4	0.3	9
60	0.8	2	41	4	2	6	0.4	0.4	8
70	0.2	1	66	4	3	5	0.3	0.4	11
80	0.5	1	66	4	3	3	0.3	0.4	10
90	0.6	0.6	72	5	3	3	0.4	0.4	10
100	0.6	0.4	199	4	3	3	0.4	0.3	13

species reproduction success by ecological land type
a quantitative baseline against which to evaluate appropriate model performance

A calibration baseline (e.g., the species proportion targets that we described in the Methods section) is used to appropriately calibrate the model. Long-term databases suitable for evaluating long-term species dynamics are exceedingly rare. The best sources available were examples of undisturbed old-growth forests and mature, lightly disturbed second-growth forests. Except for extreme events such as tornadoes, information on the extent of wind disturbance to forests is virtually nonexistent. Even with the best available data, calibration of LANDIS (or similar long-term, landscape-scale simulation models) will require a combination of inventory data and professional judgment.

After model calibration, information needed to initialize and implement LANDIS may still be hard to find and/or create. Application of LANDIS requires a raster map of ecological land units (often based on a local ecological land classification system) and a map of the initial vegetation conditions (species presence/absence by age class for each site). There are few places where this information has been assembled in sufficient detail to initialize LANDIS for a large, contiguous landscape. Application of the harvest algorithms requires additional maps of stand boundaries and management unit boundaries.

One of the most powerful aspects of this methodology is the ability to simulate a wide variety of fire, wind, and harvest disturbances in a spatially explicit manner (i.e., on a mapped landscape). The LANDIS software provides methods to alter the size, frequency, and severity of fire and wind events. It also provides a means to map and display the simulated wind, fire, and harvest disturbances over time. Outputs can be further analyzed by standard GIS software.

Although the exact locations of future wind and fire disturbance cannot be predicted with accuracy, the overall pattern of these events across the landscape through time provides new insights into forest dynamics. Maps displaying general patterns of disturbance through time convey different information than numeric tabulations traditionally compiled from forest inventory plots and used to predict and analyze forest change. For example, statistics indicate that with current levels of fire suppression, a given hectare of forest will burn once every 300 years. However, a map of cumulative fire events (fig. 4) clearly shows that (1) fire will affect about one-third of the landscape over the course of a 100-year planning cycle, and (2) some fires will be severe enough to result in stand reinitiation. The probable impacts of future fire disturbance must be factored into management plans that try to regulate the area of early-successional forest. Without maps of cumulative fire and wind impacts on forest age structure over time, the potential impact of expected fire disturbances is easily overlooked.

For many landscapes, effects of harvest on forest structure will far exceed the impact of natural disturbances. The harvest algorithms recently added to LANDIS are extremely flexible and can simulate a great variety of harvest patterns (Gustafson *et al.*, in prep.). The user can specify the time of harvests, percentage of the landscape affected, regions where harvests will be located, species and age classes to remove, and size of harvest openings. The major reproduction systems can be simulated including uneven-aged management by group selection (group opening size must be ≥ the size of one pixel) and even-aged management by clearcut, shelterwood, or seedtree harvest. Harvests may be constrained to follow stand boundaries and to avoid removals in adjacent stands. Sites may be selected for harvest based on a variety of ranking algorithms including stand age and estimated product values. Harvests may be restricted to specific age cohorts and species groups. The ability to visualize, analyze, and summarize patterns of forest age and size distribution in response to timber harvest is essential in forest planning. It is also prerequisite to analyzing effects of disturbance on other ecosystem attributes such as wildlife habitat quality, economic value, or aesthetic quality that are dependent on forest vegetation.

The internal representation of overstory vegetation in LANDIS as simply the presence (or absence) of a given species by age class is sufficiently detailed for many large-scale simulation problems. But the lack of traditional measures of stand (or site) density by species can complicate how the results are used and interpreted. Logically, one might simply link each stand (or each site) on the initial landscape map to a conventional stand inventory that includes tree-level detail. Then tree-based forest growth and yield models such as TWIGS (Miner *et al.* 1988), Prognosis (Wykoff *et al.* 1982), or FVS (Teck *et al.* 1996) could be used to forecast detailed changes in the forest structure and species composition with or without management. Although such an approach would be elegant in its simplicity and compatibility with existing inventory systems, several operational problems currently limit implementation of that methodology. Most tree-based simulation models lack the ability to predict ingrowth and to simulate long-term successional changes in the absence of disturbance. Nor can they simulate the effects of wind and fire disturbance on individual trees. LANDIS is able to minimize these problems by minimizing the amount of tree-level detail that is associated with a given site. Also, linking a tree-based forest projection model to a landscape simulation system would require far more computational resources than are required by

LANDIS. However, over time, computing resources will increase and the computational limitations will be far less of a problem than the issue of how to model wind and fire disturbance effects on individual trees.

Application of LANDIS is computationally intensive. Simulations like the ones presented as examples in this paper can be completed in a few minutes after all files are prepared. However, the largest mapped landscape in Missouri encompasses approximately 200,000 ha. For that landscape, a single 100-year simulation with management can take 8 hours on a medium-size workstation, exclusive of input map preparation and subsequent analysis of results. Output maps and summaries can exceed several gigabytes of storage.

LANDIS is not a simple program to operate. The user-interface continues to improve and simplify the process of adjusting parameters and managing files. However, the program is complex. The user has the flexibility to adjust the fire, wind, and harvest disturbance processes as well as the parameters that regulate species dynamics within the model. Intelligent exercise of that control requires an understanding of how the algorithms work and how they interact at the species level. For example, a small reduction in reproduction probability for one species may lead to large increases in presence of another species that has similar life-history characteristics. These and other subtle insights related to initializing landscape conditions and interpreting results are best learned through extensive trial simulations and interaction with LANDIS developers or other users.

The outcome of any given landscape simulation is the net result of thousands or even millions of stochastic events. Within LANDIS, species establishment on each site, mortality, fire location, fire severity, and sprouting after disturbance are all simulated as event probabilities. Consequently, due to stochastic variation, repeated simulations on the same landscape will result in slightly different patterns of disturbance and vegetation response. This directly reflects the uncertainty associated with projections of natural disturbances. Due to the stochastic nature of the processes involved, repeat runs of the same scenario provide a mechanism to examine variation in the simulated landscape and the opportunity to compute probabilities for outcomes of special interest.

Users of long-term simulation results need to be cognizant of other social, political, and ecological factors that may affect disturbance patterns in future decades. Population shifts across the landscape, changes in forest land ownership, laws regulating harvest practices, attitudes about the role of fire in ecosystems, introduction of new pests (e.g., gypsy moth), and development of new utilization technologies (e.g., chip mills) could greatly affect future disturbance patterns on a forest landscape. These effects should be considered in the development of simulated disturbance scenarios. The LANDIS simulation environment is sufficiently flexible to accommodate simulation scenarios that incorporate assumptions about the future impact of these and other potential disturbance processes over the coming decades.

The next step in applying these results to forest management is the development of linkages to other ecosystem attributes of interest. Some attributes are easier to derive than others. Timber yields through time can be estimated from local or regional yield tables applied to the simulated harvest patterns. These can even be adjusted for known differences in site quality in different ecological land types. Converting timber yield to dollar values is also straightforward. Recent information about the relationship of down wood to disturbance patterns and stand age in central hardwood forests (Jenkins and Parker 1997) provides a means to link stand age and disturbance history to the volume of down wood. Even general levels of scenic beauty can be linked to the age and disturbance history of a forest site (Hetherington and Burde 1977). Linking landscape simulation results to key wildlife species generally requires more complicated linkages and the application of ancillary models to the simulated landscape conditions.

ACKNOWLEDGMENTS

We thank Bill Dijak for his capable assistance with the simulation runs and graphics presented in this paper. We thank Kevin Nimerfro for the insightful programming enhancements that allowed simulation of harvest alternatives. We are grateful to John Kabrick, Missouri Department of Conservation, Columbia, MO, and Mary Ratnaswamy, School of Natural Resources, University of Missouri, Columbia, MO, for their review of this manuscript.

LITERATURE CITED

Brookshire, B.; Hauser, C. 1993. The Missouri Forest Ecosystem Project. In: Gillespie, A.R.; Parker, G.R.; Pope, P.E.; Rink, G., eds. Proceedings, 9th Central hardwood forest conference. Gen. Tech. Rep. NC-161. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 289-307.

Brookshire, B.L.; Jensen, R.; Dey, D.C. 1997. Design of the Missouri Ozark Forest Ecosystem Project (MOFEP). In: Brookshire, B.L.; Shifley, S.R., eds. Proceedings of the Missouri Ozark Forest Ecosystem Project symposium: an experimental approach to landscape research. Gen. Tech. Rep. NC-193. St.

Paul. MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 1-25.

Brookshire, B.L.; Shifley, S.R. 1997. Proceedings of the Missouri Ozark Forest Ecosystem Project symposium: an experimental approach to landscape research. Gen. Tech. Rep. NC-193. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 378 p.

Gustafson, E.J.; Shifley, S.R.; Mladenoff, D.J.; Nimerfro, K.K. In preparation. Simulating timber harvest and forest succession using LANDIS.

Guyette, R. 1996. A tree-ring history of wildland fire in the Current River watershed. Columbia, MO: School of Natural Resources, University of Missouri.

Guyette, R.P.; Dey, D. 1997. Fire and logging history at Huckleberry Hollow, Shannon County, Missouri. Forest Res. Rep. 1. Jefferson City, MO: Missouri Department of Conservation. 10 p.

He, H.S.; Mladenoff, D.J. In press. Dynamics of fire disturbance and succession on a heterogeneous forest landscape: a spatially explicit and stochastic approach. Ecology. 80(1): 81-99.

He, H.S.; Mladenoff, D.J.; Boeder, J.E. 1996. LANDIS: a spatially explicit model of forest landscape change. LANDIS 2.0 user's guide. Madison, WI: Department of Forestry. University of Wisconsin-Madison.

Hetherington, J.; Burde, J. 1997. Perceived impacts of disturbance in central hardwood ecosystems. In: Pallardy, S.G.; Cecich, R.A.; Garrett, H.G.; Johnson, P.S., eds. Proceedings of the 11th central hardwood forest conference. Gen. Tech. Rep. NC-188. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 47.

Jenkins, M.A.; Parker, G.R. 1997. Changes in down deadwood volume across a chronosequence of silvicultural openings in southern Indiana forests. In: Pallardy, S.G.; Cecich, R.A.; Garrett, H.G.; Johnson, P.S., eds. Proceedings of the 11th central hardwood forest conference. Gen. Tech. Rep. NC-188. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 162-169.

Keane, R.E.; Menakis, J.P.; Long, D.; Hann, W.J.; Bevins, C. 1996. Simulating coarse scale vegetation dynamics with the Columbia River Basin Succession Model—CRBSUM. Gen. Tech. Rep. INT-340. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 50 p.

Mcgaughey, R.J. 1998. Techniques for visualizing the appearance of forest operations. Journal of Forestry. 96: 9-14.

Mcgaughey, R.J.; Ager, A. 1996. UTOOLS and UVIEW: analysis and visualization software. In: Proceedings of the Sixth Biennial USDA Forest Service Remote Sensing Application Conference; 1996 April 29-May 3; Denver, CO. Bethesda, MD: American Society of Photogrammetry and Remote Sensing: 319-329.

Miller, M.R. 1981. Ecological land classification terrestrial subsystem, a basic inventory system for planning and management on the Mark Twain National Forest. U.S. Department of Agriculture, Forest Service, Eastern Region. 87 p.

Miner, C.L.; Walters, N.R.; Belli, M.L. 1988. A guide to the TWIGS program for the north central United States. Gen. Tech. Rep. NC-125. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 105 p.

Mladenoff, D.J.; Host, G.E.; Boeder, J.E.; Crow, T.R. 1996. LANDIS: a spatial model of forest landscape disturbance, succession, and management. In: Goodchild, M.F.; Steyaert, L.T.; Parks, B.O., eds. GIS and environmental modeling: progress and research ideas. GIS World Books: 175-179.

Mowrer, T.W., tech. comp. 1997. Decision support systems for ecosystem management: an evaluation of existing systems. Gen. Tech. Rep. RM-296. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 154 p.

Shifley, S.R. 1994. Old growth forests in the central states: observations on a unique resource. In: Foresters together: meeting tomorrow's challenges. Society of American Foresters National Convention Proceedings; 1993 November 7-10; Indianapolis, IN. Bethesda, MD: Society of American Foresters: 527-528.

Shifley, S.R.; Brookshire, B.L.; Larsen, D.R.; Herbeck, L.A. 1997. Snags and down wood in Missouri old-growth and second-growth forests. Northern Journal of Applied Forestry. 14: 165-172.

Shifley, S.R.; Roovers, L.M.; Brookshire, B.L. 1995. Structural and compositional differences between old-growth and mature second-growth forests in the Missouri Ozarks. In: Gottschalk, K.W.; Fosbroke, S.L.C., eds. 10th Central hardwood forest conference proceedings. Gen. Tech. Rep. NE-197. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 23-36.

Teck, R.M.; Moeur, M.; Eav, B. 1996. Forecasting ecosystems with the forest vegetation simulator. Journal of Forestry. 94(12): 7-10.

Westin, S. 1992. Wildfire in Missouri. Jefferson City, MO: Missouri Department of Conservation. 161 p.

Wykoff, W.R.; Crookston, N.L.; Stage, A.R. 1982. User's guide to the stand Prognosis Model. Gen. Tech. Rep. INT-133. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 112 p.

Annual Updating of Plantation Inventory Estimates Using Hybrid Models

Peter Snowdon

Abstract.—Data for *Pinus radiata* D. Don grown in the Australian Capital Territory (ACT) are used to show that annual indices of growth potential can be successfully incorporated into Schumacher projection models of stand basal area growth. Significant reductions in the error mean squares of the models can be obtained by including an annual growth index derived from estimates of photosynthesis simulated with a detailed process-based model: BIOMASS. In the ACT, it was sufficient to estimate the growth index at a single location within the forest estate.

Predictions made with models containing indices of temporal variation in growth potential were less biased and more accurate than those obtained without including climatic information. The new models improve descriptive power of the models and open up new avenues for forest modeling. They are particularly applicable for making short-term updates of forest inventories.

Builders of management-oriented growth models have shown considerable ingenuity in developing projection equations with additional variables (for example, site index, time, and amount of thinning) to enhance the quality of predictions. Other variables that account for spatial variation in climatic or edaphic factors have not been greatly used partly because of the unavailability of data at sufficient spatial intensity for use with traditional inventory sample plot data. In recent years, many forestry organizations have acquired detailed soil information for their forest estates so that site-specific management regimes can be developed. Moreover, environmental (for example, rainfall, solar radiation) data have become available, through the application of response surface splining programs to climatic data (e.g., BIOCLIM, Nix 1986) from which estimates of long-term climate averages can be made at any chosen location. Woollons *et al.* (1997) were able to show that by including such data an improvement of 10 percent could be obtained in a Schumacher projection model for stand basal area of *Pinus radiata* D. Don grown in the Nelson region of New Zealand.

Representation of temporal variation in growing conditions by year-to-year deviations from climatic averages is rarely included in models to forecast production. However, considerable work has been carried out over many years to relate climatic conditions to the growth of *P. radiata* in the Australian Capital Territory (ACT). In the 1980's, a comprehensive, multidisciplinary, field experiment studying the effects of water and nutrients on the growth of *P. radiata* was carried out in the ACT. One of the key results was the development of a detailed process-based model (BIOMASS) for the growth of *P. radiata* (McMurtrie *et al.* 1990). It was noted that a great deal of work would be required before BIOMASS would provide a reliable management tool for forest management and that a serious limitation was the high data input requirements (McMurtrie and Landsberg 1992). One solution to this was obtained by relaxing some of the input requirements for BIOMASS (see below) and by using various outputs from the model as annual growth indices. Such indices have been successfully incorporated into a logarithmic-reciprocal model in its projection or difference form that was used to model height, basal area, and volume increment in a trial in which *P. radiata* was planted at different stocking rates (Snowdon *et al.* 1998a).

In this paper, the results of Snowdon *et al.* (1998a) are summarized and extended by including annual variation in climatic-based factors into projection models for annual basal area increment of *Pinus radiata* grown in the ACT. It is shown that temporal variation in the growth indices need only be estimated at a single site. A Monte Carlo method is used to compare bias, precision, and accuracy of predictions made with the various models.

METHODS

Growth Data and Site Information

Three sets of data from *Pinus radiata* grown in the ACT are used: (a) height, basal area, and volume data from 4 to 16 years of age in an experiment testing six spacing densities (Snowdon *et al.* 1998a); (b) 444 observations of

---

Senior Research Scientist, CSIRO Forestry and Forest Products, P.O. Box E4008, Kingston ACT 2604, Canberra, Australi

annual basal area increment in stands from 5 to 50 years of age from 20 permanent sample plots (PSP) during 1936 to 1984 (Snowdon *et al.* 1998b); and (c) 1,728 observations of annual basal area increment by combining set (b) with data from 42 additional PSP. The plots were located at 600 to 800 m altitude at about latitude 35° 20' S. Average annual rainfall varied from 645 to 1,120 mm. For each plot in data sets (a) and (b), a detailed soil characterization was made including an estimation of field capacity, wilting point, and plant available water in the soil.

Estimation of Annual Growth Index

Daily records taken of rainfall, maximum temperature, and minimum temperature were available from four meteorological stations each representing a local plantation working circle. The systematic differences in annual climatic averages between the nearest meteorological station and each of the permanent sample plots in the data set were estimated from regional climatic surfaces (BIOCLIM, Nix 1986) based on latitude, longitude, and altitude. These differences were then applied to the measured meteorological data to estimate daily rainfall and temperatures at each plot.

The process-based model BIOMASS (McMurtrie *et al.* 1990) requires input of seasonal measurements of leaf area index (LAI) and other canopy characteristics. Here, a simplified non-varying canopy structure in the simulations is used: complete canopy closure, a fixed LAI of 5.0, and a crown depth of 10.75 m. Physiological parameters appropriate for *Pinus radiata* and soil moisture characteristics determined for each site were used. The simulations were carried out using daily data for rainfall, maximum temperatures, and minimum temperatures. Annual photosynthetic carbon fixation (P) was then used as a climatic index.

Climatic Indices

As shown by Snowdon *et al.* (1998a), each of the annual observations of a climatic index (CI_i) such as annual rainfall or estimated annual carbon fixation can be regarded as being composed of two components: a long-term average value ($\underline{CI}$) and an annual deviation (Δ_i) from that value. Thus

$$CI_i = \underline{CI} + \Delta_i \qquad (1)$$

These terms can all be scaled by dividing by the mean ($\underline{CI}$) to give a scaled climatic index (SCI_i):

$$SCI_i = 1 + \Delta_i / \underline{CI} \qquad (2)$$

The sum of the scaled climatic index from the planting until a given plantation age is given by

$$\begin{aligned} \Sigma\, SCI_i &= \Sigma\,(1 + \Delta_i / \underline{CI}) \\ &= \text{Age} + \Sigma\, \Delta_i / \underline{CI} \qquad (3) \end{aligned}$$

Both scaled deviations ($\Delta_i / \underline{CI}$) and their sum ($\Sigma\, \Delta_i / \underline{CI}$) are used in the models described below. Note that within the data set used to define the mean ($\underline{CI}$) the scaled deviations have a mean of zero and their sum tends to zero.

In the following discussion, the symbol CI will be used to refer to the scaled deviations of a growth index while S CI will refer to their sum from planting until the year of observation.

Schumacher Growth Model

The basic model used in this study was the modified Schumacher log-reciprocal model of forest growth (Clutter *et al.* 1992) in its projection or difference form:

$$Y_2 = \exp(\log(Y_1)(T_1/T_2)^b + a(1 - (T_1/T_2)^b)) \qquad (4)$$

where Y_1, Y_2 are current and future stand size corresponding to ages T_1, T_2 respectively, a is estimated maximum yield parameter, and b is a shape parameter. The basic equation can be extended by exchanging the constants a, b with functions A, B and by replacing (T_1/T_2) with (C_1/C_2), where the denominator and numerator have the same functional form $C_i = T_i + q_j X_j$, with i taking the value 1 or 2, and q_j being functions of X_j additional predictive variables (Snowdon *et al.* 1998a).

In this paper we investigate four classes of equations in which:

1. the basic Schumacher model in which the asymptote, A, is a constant; B is a constant; and $C_i = T_i$;
2. A and B as in 1., but with the time function, C, now augmented with the sum of the deviations of the climate index since plantation establishment, i.e., $C_i = T_i + a\, \Sigma\, CI$ where a is a constant;
3. A, B, and C as in 1. but with the additional incorporation of scaled deviations of the climatic indices, (CI), into the asymptote function, i.e., A = c + d CI;
4. A as in 3., C as in 2., and B as a constant.

These basic models are also examined after the asymptote function has been augmented with continuous variables representing spatial variation in plot elevation (data set a) or site index (data set c). In data set (a), shape function, B, is also a function of stocking; and the time function, C, incorporates a constant that represents the time delay until trees have a measurable breast high diameter.

The study is restricted to annual increments, that is, cases where $T_2 - T_1 = 1$.

Simulated Sampling Study

A Monte Carlo re-sampling method was used to test the ability of the various models to predict stand increment. This was achieved by constructing samples that contained one randomly chosen measurement from each plot. One hundred samples were constructed. The data in each sample were used to estimate parameters in each of the equations developed above. Each equation within each sample set was used to predict increment for the whole data set. The results from these enable three criteria to be used to compare the models. Bias was estimated by the mean difference between estimates of total annual increment obtained by simulation and its known true values. Precision, or the size of deviations from the biased mean obtained by repeated application of the sampling procedure, was estimated by the standard deviation of the estimates. Accuracy, a measure of the size of deviations from the true mean, was estimated by the formula (Cochran 1963):

$$\text{accuracy}^2 = \text{bias}^2 + \text{precision}^2 .$$

For convenience all three measures are expressed here as percentages. Both precision and accuracy are said to increase when their associated numerical values decline.

RESULTS

Variation in the Growth Index

The 48-year average for the climatic index derived from BIOMASS ranged from 17.3 to 29.9 tonnes of carbon per hectare (t C ha^{-1}) between sites (PSP). On the best site, annual variation was in the range +/- 15 t C ha^{-1}, while on the poorest it was about +/- 9 t C ha^{-1}. Variations of this magnitude would be expected to result in large variations in growth between sites and between growing seasons.

Growth in a Spacing Trial

The functions in the complete model for volume increment, which included a growth index in both the asymptote functions, took the form

$$A = a + d\,CI + f\,Elevation$$
$$B = b + g\,Stock$$
$$C = T - (c + h\,Stock) + k\,\Sigma\,CI$$

where a, b, c, d, f, g, h are constants, and Elevation is local plot elevation (range 14 m) and Stock is planting density (1,000s stems ha^{-1}). Volume increment observed in three treatments from the experiment is illustrated in figure 1a. Annual increments predicted by the basic Schumacher model (in which d=k=0, EMS=9.91) are shown in figure 1b, while those predicted by the complete model with a growth index in the time and asymptote function (EMS=5.30) are shown in figure 1c. The improvement in fit can be judged by the reduction in EMS. Table 1 summarizes the percentage reduction in mean squares obtained by including the growth index into the basic models (including elevation where appropriate) for annual increments in height, basal area, and volume. Including the climatic index in the asymptotic function was always better than including it in the time function, but the best models had expressions of the indices in both functions.

Comparison of Climatic Indices

Models including a term for site index in the asymptote were developed for annual basal area increment in 20 PSP in the region. A test was made to determine if a climatic index P evaluated at a single representative site could be used as the index for all sites. The PSP chosen was close to one of the meteorological stations (Uriarra) and was close to the averages of all plots with respect to annual rainfall and climatic index P. Correlations of the growth index obtained at this site with 19 other sites were between 0.87 and 1.00 with an average of 0.94. Application of a single index resulted in only a small inflation of the EMS for the various classes of models (table 2). This is a key result because it eases the burden of large and detailed data requirements necessary as input to process-based models such as BIOMASS, which has precluded their use for day-to-day forest management applications.

Bias, Precision, and Accuracy of Predicted Annual Basal Area Increment

The finding above allowed the larger data set to be used in conjunction with a growth index estimated at a single site. The sample was sufficiently large so that a Monte Carlo re-sampling method could be used to avoid problems arising from correlated errors in the data. Percentage bias, precision, and accuracy for annual basal area increments predicted by the various models are given in table 3. Average annual basal area increment was 1.9 m^2ha^{-1}.

None of the models produced predictions that were significantly ($p<0.05$) biased. These results were obtained with the complete data set, which contained observations for which the growth index varied markedly from year to year, i.e., they are an index of average performance over a wide range of growing conditions. To determine the effectiveness of the models to predict basal area increment in different climatic circumstances, five subsets of the data based on increasing magnitudes of the growth index

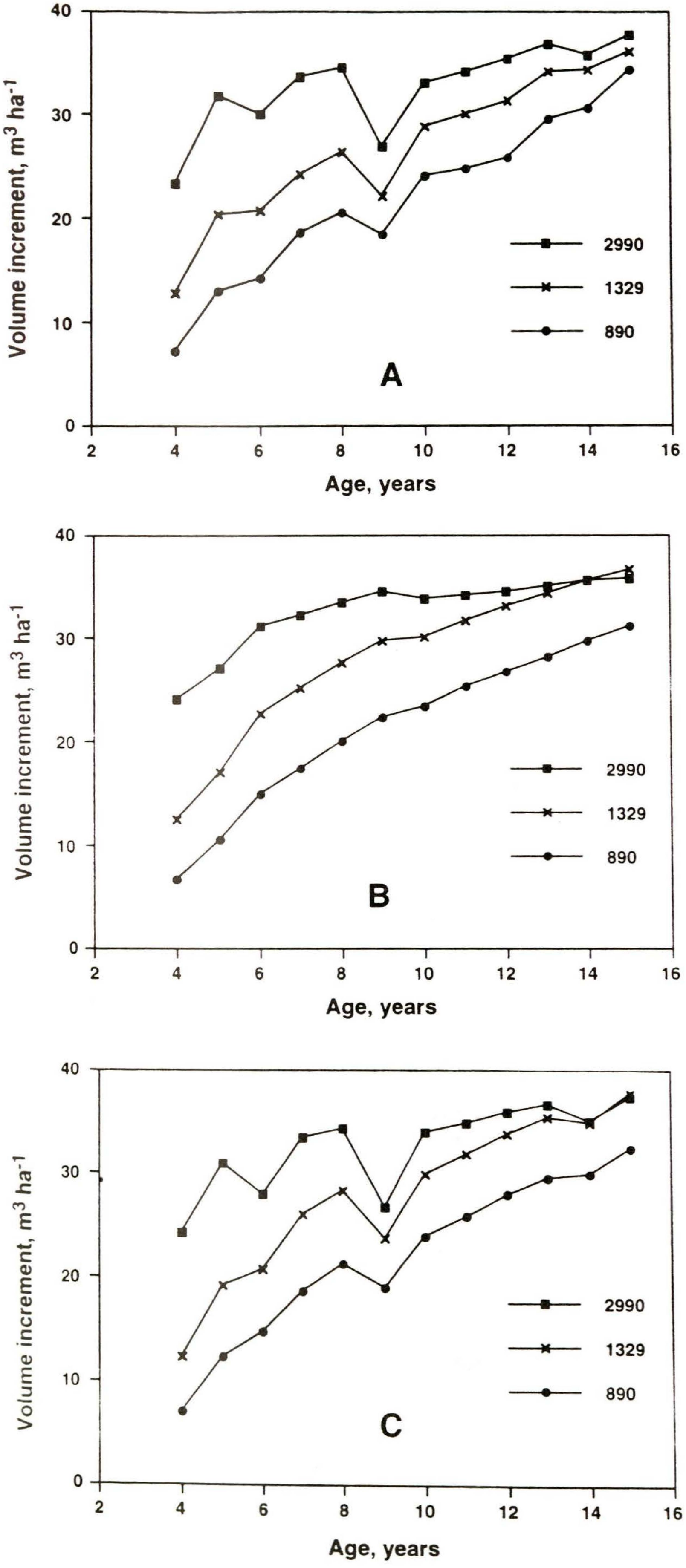


Figure 1.—*Observed annual volume increment of* Pinus radiata *grown at different stockings* (**A**)*, and predictions made with the basic Schumacher model (***B**)*, and the modified model* (**C**) *containing climatic indices in the asymptote and time functions.*

Table 1.—*Percentage reduction in error mean squares obtained by including the growth index obtained from BIOMASS into the time and asymptote functions of the Schumacher equation*

Function	Height	Basal area	Volume
Time	6.8	12.3	25.8
Asymptote	7.7	28.7	32.7
Time and asymptote	21.4	38.6	46.5

Table 3.—*Bias, precision, and accuracy of various models used to predict annual basal area increment in 62 permanent sample plots of* P. radiata

Model	Bias	Precision	Accuracy
a) Basic	-0.61	3.17	3.23
b) Asymptote	-1.80	2.38	2.98
c) Time	-1.65	2.25	2.79
d) Complete	-1.80	2.52	3.10

were derived. The values of bias, precision, and accuracy for predictions made with the basic model and those containing temporal components are illustrated in figure 2. The basic model greatly overestimated ($p < 0.01$) annual increment when the growth index was low and greatly underestimated ($p < 0.01$) increment when the index was high. There was only a small region, between + 5 and - 5 percent predicted bias, where bias was not significantly different from zero. Thus, the small bias in the estimates of increment obtained with the basic model using the complete data set arise from compensatory balances between overestimates and underestimates. The biases for models containing temporal parameters were only significantly biased for the central subset of the data.

Precision for all models tended to take a parabolic form with their minimal values near the average value of the growth index. The precision for the predictions from the basic model tended to have a flatter parabolic form than those obtained with models containing temporal variables. Accuracy of models containing temporal variables was relatively constant throughout the whole range of the growth index, but comparable levels of accuracy were obtained with the basic model only when the growth index approached average values.

DISCUSSION

Applications

Forest managers need accurate and timely information to make decisions. Considerable research has been directed at refining models for this purpose with emphasis placed on those in projection form. It is particularly important that the models should provide unbiased predictions. As shown above (fig. 2), the basic Schumacher model can be seriously biased when it is used for specific short-term predictions in regions where there are large year-to-year differences in growing conditions.

It has not been usual to take account of temporal variation of growth in forestry growth models. Temporal variation in climatic factors cannot be reliably predicted for future years so the inclusion of temporal variables into growth models would seem, at first sight, to be a futile exercise. This is not the case. A complete forest inventory is rarely carried out across the entire forest estate on an annual basis, but timely information on the forest resource may be needed at any time (e.g., Van Deusen 1997). Double sampling, in which some plots are re-measured, is often used, but models are sometimes used to update the previous inventory to the current time. In the latter case the weather conditions during the intervening period are known, so more accurate updates can be achieved by including temporal variables in the model. The inclusion

Table 2.—*Effect of various indices of climatic variation on the reduction of error mean squares of modified Schumacher models of annual basal area increment in 20 permanent sample plots of* P. radiata

	Model			
	Basic	Time	Asymptote	Both
Indices for each plot	0.2693	0.1976	0.1842	0.1800
Single index	0.2693	0.2033	0.1886	0.1789

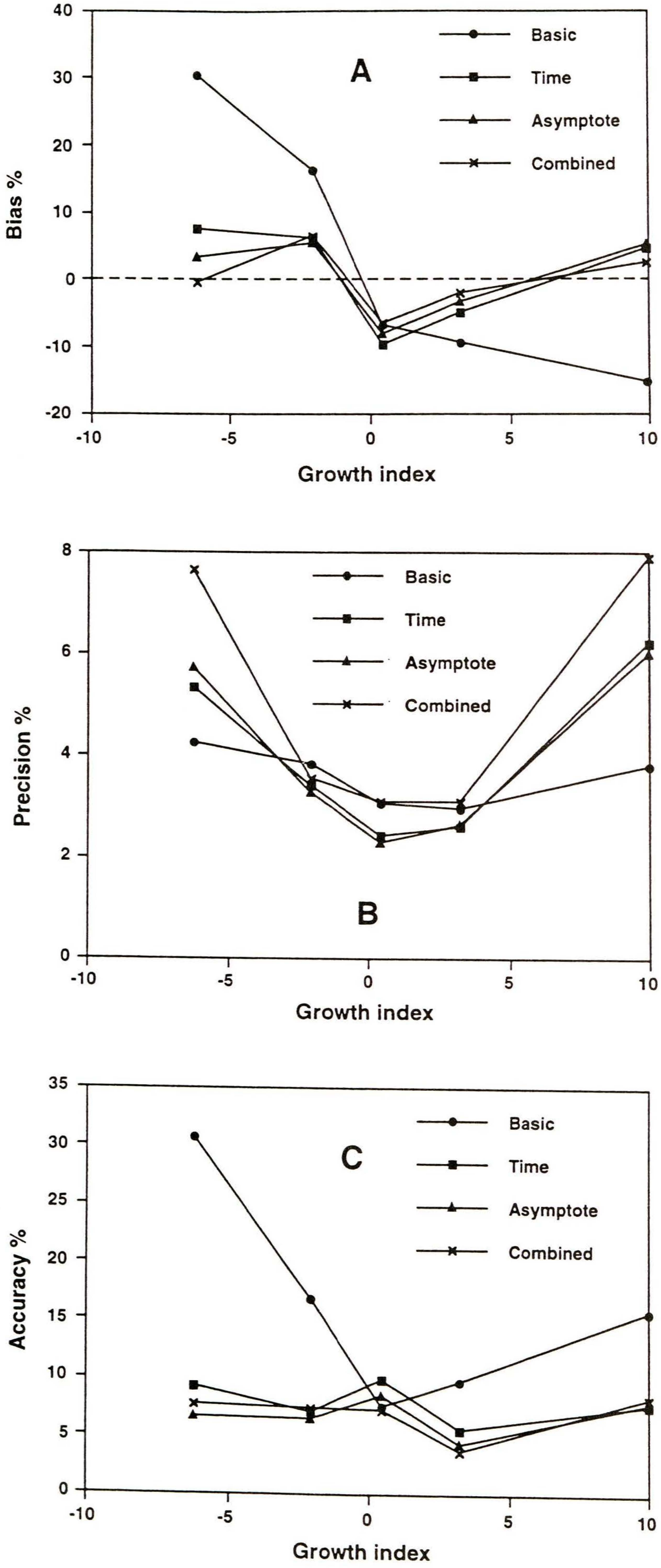


Figure 2.—*Bias* (**A**), *precision* (**B**), *and accuracy* (**C**) *of predictions of annual basal area increment made with basic and modified Schumacher models at different values of the climatic index.*

of temporal variables opens up the possibility of forecasting growth according to various hypothetical climatic scenarios. If a detailed process-based model has been used, then the effects of important changes, such as increasing atmospheric carbon dioxide concentrations, can be examined.

Properties of the Models

Ideally, models used for estimation of growth and yield in forests should be compatible and path invariant (Clutter *et al.* 1992). As is well known, the projection or difference equations used in this study are all compatible. Those equations that do not include an annually variable growth index in the asymptote function, A, are all path invariant because for each age and stocking there is a unique value for the function C. When an annually variable growth index is included in A, the projections must be iterated annually. This need not be a disadvantage for prediction because such computations can now be easily and rapidly made. Incorporation of temporal factors into the models increases bias in predictions, but these are not statistically significant for predictions of annual growth (table 3). Annual observations of climate-based indices or those derived from processed-based models are required for calibration of the growth models. In the case of path invariant models, these are required so that the sum of the deviations from the long-term average can be calculated. When the temporal variable is included in the asymptote function, annual growth measurements are also required.

Various indices can be used to capture the essence of seasonal differences in growth potential. Good improvement can be obtained by using a simple index such as growth season rainfall (Snowdon *et al.* 1998 a,b) but better results can usually be obtained by using an index derived from a process-based model such as BIOMASS. The superiority of this growth index compared to rainfall can be attributed to the ability of the BIOMASS model to integrate the effects of seasonal differences in climatic factors such as temperature, rainfall, and evaporative demand with changes in soil water storage and thereby the effectiveness of photosynthetic production in different growth periods. Thus, a dry period during winter may have little effect on the growth index while a wet period during summer would have a large effect. Annual rainfall weights each rainfall event equally.

In this study it was sufficient to use a growth index calculated at a single location to capture temporal variability for the entire regional data set. Although there is considerable spatial variability in climatic averages, particularly for rainfall, across the region, the climatic data are highly correlated. Consequently, the relative suitability of conditions for producing stand growth during a growth season is also highly correlated across the region. This is an important property when the models are used to predict growth on plots established for inventory purposes. The number of plots used for inventory usually far exceeds the number of plots used to calibrate the model. Consequently, it is important that the input data for the model (stand age, initial basal area, site factors, growth indices, etc.) be quickly and cheaply estimated. Use of a single, regional index of climatic variation avoids the need for time-consuming calculation of an index for each inventory plot.

The best index in these studies was estimated by using a detailed process-based model of photosynthetic carbon fixation with simplified assumptions about canopy structure. Simplification was necessary because there were no historic data about canopy cover or structure. It is likely that the index could be improved if estimates of leaf area index were available. In the case of existing data, the estimates would need to be made with a mathematical model based on stand and site characteristics. In existing stands, rapid but reliable estimates can be made by eye (Sampson *et al.* 1996). Spatial variables, such as site index, topographic position, spatial averages of climatic and growth indices, geological substrate, and indices of soil development, can also be included in the models to reduce EMS (Snowdon *et al.* 1998 a,b). The effects of spatial and temporal classes of variables are approximately additive.

CONCLUSIONS

Substantial improvement in prediction of annual basal area growth can be achieved for some forests by incorporating annual growth indices derived from detailed process-based models into Schumacher difference equations. Short-term predictions made with these models are more accurate than those obtained with the traditional model and are particularly useful for updating stand inventories. The new models should be most applicable to regions where there is substantial variation in climatic factors from season to season and where the object species is responsive to those factors.

The approach can broaden the scope of forestry modeling and will be of increasing importance as quantification of the forest estate becomes more detailed and forest managers become increasingly reliant upon geographic information systems in making their decisions.

ACKNOWLEDGMENTS

The author wishes to thank the staff of the ACT Forests Branch for permission to use their growth data.

The following people reviewed this manuscript: Nicholas Coops, CSIRO Forestry and Forest Products, Clayton South, VIC, Australia, and Richard Woollons, University of Canterbury, Christchurch, New Zealand.

LITERATURE CITED

Clutter, J.L.; Fortson, J.C.; Pienaar, L.V.; Brister, G.H.; Bailey, R.L. 1992. Timber management: a quantitative approach. (Reprint edition). Malabar, FL: Krieger Publishing Company.

Cochran, W.G. 1963. Sampling techniques, 2d ed. New York: John Wiley & Sons. 411 p.

McMurtrie, R.E.; Rook, D.A.; Kelliher, F.M. 1990. Modeling the yield of *Pinus radiata* on a site limited by water and nitrogen. Forest Ecology and Management. 30: 381-413.

McMurtrie, R.E.; Landsberg, J.J. 1992. Using a simulation model to evaluate the effects of water and nutrients on the growth and carbon partitioning of *Pinus radiata*. Forest Ecology and Management. 52: 243-260.

Nix, H.A. 1986. A biogeographic analysis of Australian Elapid snakes. In: Longmore, R., ed. Atlas of Elapid snakes of Australia. Canberra, Australia: Australian Government Publishing Service.

Sampson, D.A.; Allen, H.L.; Lunk, E.M.; Blevins, D.P. 1996. The ocular LAI comparator for loblolly pine version 4.0. Forest Nutrition Cooperative, Department of Forestry, North Carolina State University, NC.

Snowdon, P.; Woollons, R.C.; Benson, M.L. 1998a. Incorporation of annual climatic indices into models of growth of *Pinus radiata* in a spacing experiment. New Forests. 15 (in press).

Snowdon, P.; Jovanovic. T.; Booth, T.H. 1998b. Incorporation of indices of annual climatic variation into growth models for *Pinus radiata*. Forest Ecology and Management. (in press).

Van Deusen, P.J. 1997. Annual forest inventory statistical concepts with emphasis on multiple imputation. Canadian Journal Forest Research. 27: 379-384.

Woollons, R.C.; Snowdon, P.; Mitchell, N.D. (1997). Augmenting empirical stand projection equations with edaphic and climatic variables. Forest Ecology and Management. 98: 267-275.

Maximum Size-Density Relationships for Mixed-Hardwood Forest Stands in New England

Dale S. Solomon and Lianjun Zhang

Abstract.—Maximum size-density relationships were investigated for two mixed-hardwood ecological types (sugar maple-ash and beech-red maple) in New England. Plots meeting type criteria and undergoing self-thinning were selected for each habitat. Using reduced major axis regression, no differences were found between the two ecological types. Pure species plots (the species basal area greater than 70 percent of the total plot basal area) were identified for six major hardwood species, and corresponding size-density relationships were developed. Results showed that shade tolerant and intermediate species had similar intercept and slope coefficients for the maximum size-density line. No differences were found between each species and habitat types; however, shade intolerant species had smaller intercept and slope coefficients than others. The two ecological types were combined, and one maximum size-density relationship was constructed for mixed-hardwood stands.

Self-thinning is an important and fundamental process during stand development. As the individual trees in a stand grow in size, trees begin to compete for resources such as water, light, and mineral nutrients. Crowding or competition occurs when the density of a forest stand exceeds the level at which each tree can obtain its maximum growing space. Natural mortality results when the minimum growing space requirements of all trees exceed the resources of the site. The dynamic equilibrium between tree growth and death at crowding density is governed by the so-called -3/2 power law of self-thinning (Drew and Flewelling 1977). The law states that in logarithm scale the relationship between average tree size and stand density is a straight line (called the self-thinning line) for a fully stocked stand undergoing density-related mortality. The line has been commonly expressed by the following mathematical equations:

$$\ln(MV) = a - 1.5 * \ln(TPA) \qquad [1]$$

(Drew and Flewelling 1977)

$$\ln(QMD) = b - 0.625 * \ln(TPA) \qquad [2]$$

(Jack and Long 1996)

where MV is mean tree volume, QMD is quadratic mean tree diameter, TPA is number of trees per unit area, and a and b are constants. These equations are mathematically compatible (Zeide 1987). The intercepts (a and b) of the equations vary with species, but only within narrow logarithmic limits. The slope parameters are apparently consistent regardless of species, age, and site quality.

Self-thinning has been observed in many types of plant forms (e.g., mosses, grasses, crops, shrubs, and trees), and in many types of plant populations (monocultures, mixtures, even-aged and uneven-aged stands). Primarily, the –3/2 power law applies to two instances: (1) for a single-species population of successive development stages, its growth trajectory over time will follow the -3/2 self-thinning line, which describes the mean tree size and density relationship of the single stand at different times; and (2) for all populations of the same species composition, regardless of stand ages and site qualities, there is a maximum possible combination between the mean tree size and the number of trees per unit area defined by the -3/2 power law. This is known as the upper boundary or maximum size-density relationship (Jack and Long 1996). It is a static relationship among stands observed at single points of time and describes the upper limiting boundary of all possible combinations of mean tree size and density.

One application of the -3/2 power law of self-thinning in forest management practices has been to derive relative stand density. It is usually expressed as a percent of absolute stand density to the reference level based on average maximum competition (Ernst and Knapp 1985). Although there are different expressions of relative stand density measures, such as Drew and Flewelling's (1979) relative density (RD) index and Reineke's (1933) stand density index (SDI), they are highly correlated since they all are a function of tree size and density (Jack and Long 1996). The maximum size-density relationship and relative stand density measures have been used to develop stand management diagrams (e.g., Dean and Jokela 1992, Drew and Flewelling 1979, Reineke 1933) and stocking charts (e.g., Gingrich 1967; Solomon and Leak 1969, 1986). Essentially, these tools are simple average stand models that graphically characterize growth, density, and mortality at various stages of stand development. Forest

---

Project Leader, USDA Forest Service, Northeastern Research Station, Durham, NH 03824, USA; and Assistant Professor, Faculty of Forestry, State University of New York ESF, Syracuse, NY 13210, USA, respectively.

managers can use the stand density management diagrams to locate the results of different surveys of the stand and to rapidly design and evaluate alternative density management regimes. This practice will help them to maximize wood fiber yield (Dean and Jokela 1992, Kershaw and Fischer 1991) and to create favorable ecological conditions for vegetation (Barbour *et al.* 1997) and wildlife (Hayes et *al.* 1997, Lilieholm *et al.* 1993).

To date, most stand density management diagrams have been developed for western and southern coniferous species plantations or even-aged stands in North America (Newton 1997). Few studies have been conducted for deciduous or mixed forests. Kershaw and Fischer (1991) developed a stand density diagram for sawtimber-sized mixed upland hardwoods in the central United States. They found that the stand density management diagram is a useful tool that not only allows point estimation of stand stocking but also serves as a stand monitoring system in which stand development and treatments can be traced through the stand management history.

However, no maximum size-density relationships and stand density management diagrams have been published for mixed-hardwood forest stands in New England. The objective of this research project was to establish the maximum size-density relationships for the two hardwood ecological habitat types in this region: sugar maple-ash (SM-ASH) and beech-red maple (BE-RM) (Solomon *et al.* 1995). These relationships can be immediately used to establish the maximum limits of the stand density management diagrams.

DATA AND METHODS

Plot data were collected from the database used in developing FIBER 3.0 (Solomon *et al.* 1995) for the two hardwood habitat types. The plots were actually the combinations of different measurements over time of all available plots and included wide ranges of the number of trees per acre, stand total volume, mean tree volume, stand total basal area, quadratic mean tree diameter, and other stand information (table 1).

Since there is no established statistical procedures for selecting appropriate plots to estimate the two coefficients of the maximum size-density relationship, we chose the following approach to select the most fully stocked plots: assuming the **slope** of the ln(MV)-ln(TPA) relationship is -1.5, the **intercept** was determined by $k = \ln(MV) + 1.5 * \ln(TPA)$ using the plot with the largest combination of ln(MV) and ln(TPA). The determined equation was then used to compute the maximum stand density (TPA_{max}) for the mean tree volume (MV) of a given plot. The relative density index (Drew and Flewelling 1979) was calculated by TPA/TPA_{max}, where TPA is the current stand density. The RD was computed for each plot, and the plots with $RD > 0.7$ were selected for developing the maximum size-density relationship. Although this threshold was arbitrary, we chose this for two reasons: (1) any stands with the relative density index of 0.7 or higher should have been undergoing the self-thinning process and experiencing density-related mortality, and (2) sufficient number of plots would be obtained for fitting the size-density relationships.

The selected plots were separately utilized to formulate the maximum size-density relationships for each of the two hardwood habitat types. The reduced major axis (RMA) regression (Leduc 1987) was used to estimate the two coefficients of the self-thinning line. Suppose a linear regression model $y = \alpha + \beta * x$, then the RMA slope coefficient is $\beta_{RMA} = \beta / r_{yx}$, where r_{yx} is the correlation coefficient between y and x. The standard error (SE) of

Table 1.—*Summary of stand variables for the two ecological habitat types of sugar maple-ash (SM-ASH) and beech-red maple (BE-RM)*

Habitat	No. plots	Variables	Mean	Std	Min.	Max.
SM-ASH	1,043	TPA	136	50	14	399
		BA	80.9	29.6	5.0	183
		QMD	10.6	1.7	6.6	16.0
		MV	16.7	6.1	5.7	40.1
BE-RM	728	TPA	152	75	7	580
		BA	68.7	33.1	1.4	172
		QMD	9.2	1.9	5.9	21.6
		MV	14.1	7.8	3.4	90.7

Note: Std - standard deviation, TPA - trees per acre, BA - stand total basal area (ft^2/acre), QMD - quadratic mean tree diameter (inch), and MV - mean tree volume (ft^3).

β_{RMA} is equal to the SE of β. The RMA intercept coefficient is $\alpha_{RMA} = \bar{y}\ \beta_{RMA} * \bar{x}$, and the SE of α_{RMA} is equal to the SE of α, where α and β are the ordinary least-squares estimates of the regression coefficients. The model development was conducted for both ln(MV)-ln(TPA) relationship (equation [1]) and ln(QMD)-ln(TPA) relationship (equation [2]). The 95 percent confidence interval (CI) was computed for each coefficient and used to compare the two hardwood habitat types.

Specific plots were identified for the major hardwood species: sugar maple (SM) (*Acer saccharum* Marsh.), American beech (BE) (*Fagus grandifolia* Ehrh.), red maple (RM) (*Acer rubrum* L.), yellow birch (YB) (*Betula alleghaniensis* Britton), paper birch (PB) (*Betula papyrifera* Marsh.), and aspen (AS) (*Populus tremuloides* Michx.). These pure species plots were defined as the basal area of the species greater than 70 percent of the total basal area of the plot. The proposed analysis procedure above was followed to develop the size-density relationship for each species, and 95 percent confidence interval (CI) of the coefficients was used to compare the differences between the species. Because only a small number of plots were available for the two shade intolerant species (paper birch and aspen), the plots of the two species were combined.

ANALYSIS RESULTS

Comparison of the Size-Density Relationships between the Two Hardwood Habitat Types

Table 2 indicated that the 95 percent CI of each coefficient for one habitat type included the corresponding coefficient for the other habitat type. Therefore, there is no difference between the two hardwood habitat types for both slope and intercept coefficients and for both ln(MV)-ln(TPA) and ln(QMD)-ln(TPA) relationships. Consequently, one maximum size-density relationship can be used for the two hardwood habitat types.

Comparison of the Size-Density Relationships between the Pure Species Stands

Because the available number of plots for the pure species stands was limited, the 95 percent CI's for these plots were wider than those for the two habitat types (table 3). In general, there was no difference between the shade tolerant or intermediate species such as SM, BE, RM, and YB, or between each species and the two hardwood habitat types for both slope and intercept coefficients and for both ln(MV)-ln(TPA) and ln(QMD)-ln(TPA) relationships. However, the two shade intolerant species (PB and AS) had smaller slope and intercept coefficients than other species (but not statistically significant). This result agreed with other findings (Jack and Long 1996). However, this was not true for the ln(MV)-ln(TPA) relationship. We suspect that the difference might be due to the computation of tree volumes for the species and the small number of data plots.

In summary, one maximum size-density relationship can be established for the mixed-hardwood forest stands in New England. The selected plots from the two habitat types were combined to estimate the upper boundary line

Table 2.—*Comparison of the slope and intercept coefficients of the maximum size-density line between the two hardwood habitat types of sugar maple-ash (SM-ASH) and beech-red maple (BE-RM)*

Habitat	No. Plots	Slope β_{RMA}		Intercept α_{RMA}	
		ln(MV)-ln(TPA)			
SM-ASH	60	1.38	(1.27, 1.49)	10.24	(10.24, 10.80)
BE-RM	123	1.41	(1.33, 1.49)	10.34	(9.88, 10.80)
		ln(QMD)-ln(TPA)			
SM-ASH	60	0.62	(0.57, 0.67)	5.71	(5.45, 5.97)
BE-RM	123	0.60	(0.56, 0.64)	5.52	(5.30, 5.74)

Note: Numbers in the parentheses are the 95 percent confidence interval. MV - mean tree volume (ft^3), QMD - quadratic mean diameter (inch), and TPA - trees per acre.

Table 3.—*Comparison of the slope and intercept coefficients of the maximum size-density line between the six hardwood species of sugar maple (SM), beech (BE), red-maple (RM), yellow birch (YB), paper birch (PB), and aspen (AS)*

Species	No. plots	Slope β_{RMA}		Intercept α_{RMA}	
		ln(MV)-ln(TPA)			
SM	41	1.41	(1.24, 1.58)	10.24	(9.38, 11.08)
BE	24	1.31	(0.98, 1.64)	9.56	(7.85, 11.27)
RM	16	1.31	(0.95, 1.67)	9.78	(7.79, 11.77)
YB	18	1.29	(0.92, 1.66)	9.66	(7.75, 11.57)
PB+AS	14	1.38	(1.10, 1.66)	10.13	(8.52, 11.74)
		ln(QMD)-ln(TPA)			
SM	41	0.63	(0.56, 0.70)	5.71	(5.33, 6.09)
BE	24	0.63	(0.47, 0.79)	5.59	(4.79, 6.39)
RM	16	0.63	(0.45, 0.81)	5.70	(4.71, 6.69)
YB	18	0.56	(0.36, 0.76)	5.29	(4.27, 6.31)
PB+AS	14	0.46	(0.36, 0.56)	4.67	(4.‘0, 5.24)

Note: Numbers in the parentheses are the 95 percent confidence interval. MV - mean tree volume (ft^3), QMD - quadratic mean diameter (inch), and TPA - trees per acre.

using the RMA technique. The resulting models were:

$$\ln(MV) = 10.86 - 1.43 * \ln(TPA) \qquad [3]$$

$$\ln(QMD) = 6.08 - 0.66 * \ln(TPA) \qquad [4]$$

where the slope coefficients were the RMA coefficients, and the intercept coefficients were recalculated using the MV, QMD, and TPA of the plot with the largest relative density index. The observed data of the two habitat types and the pure species stands are plotted for both ln(MV)-ln(TPA) and ln(QMD)-ln(TPA) relationships (figs. 1 to 10). The maximum size-density relationships (equations [3] and [4]) are also shown as the upper boundary line in the graphics.

ACKNOWLEDGMENTS

The authors thank USDA Forest Service, Northeastern Research Station, for their support in this study. The project is also partially supported by the State of New York/UUP Professional Development and Quality of Working Life Committee. We also thank the following people for reviewing this manuscript: Dr. Jeffrey H. Gove and Mr. William B. Leak, USDA Forest Service, Northeastern Research Station, Durham, NH, and Dr. Thomas B. Brann, University of Maine, Orono, ME.

LITERATURE CITED

Barbour, R.J.; Johnson, S.; Hayes, J.P.; Tucker, G.F. 1997. Simulated stand characteristics and wood product yield from Douglas-fir plantations managed for ecosystem objectives. Forest Ecology and Management. 91: 205-219.

Dean, T.J.; Jokela, E.J. 1992. A density-management diagram for slash pine plantations in the lower coastal plain. Southern Journal of Applied Forestry. 16: 178-185.

Drew, T.J; Flewelling, J.W. 1977. Some recent Japanese theories of yield-density relationships and their application to Monterey pine plantations. Forest Science. 13: 39-53.

Drew, T.J.; Flewelling, J.W. 1979. Stand density management: an alternative approach and its application to Douglas-fir plantations. Forest Science. 25: 518-532.

Ernst, R.L.; Knapp, W. 1985. Forest stand density and stocking: concepts, terms, and the use of stocking guides. Gen. Tech. Rep. WO-44. Washington, DC: U.S. Department of Agriculture, Forest Service.

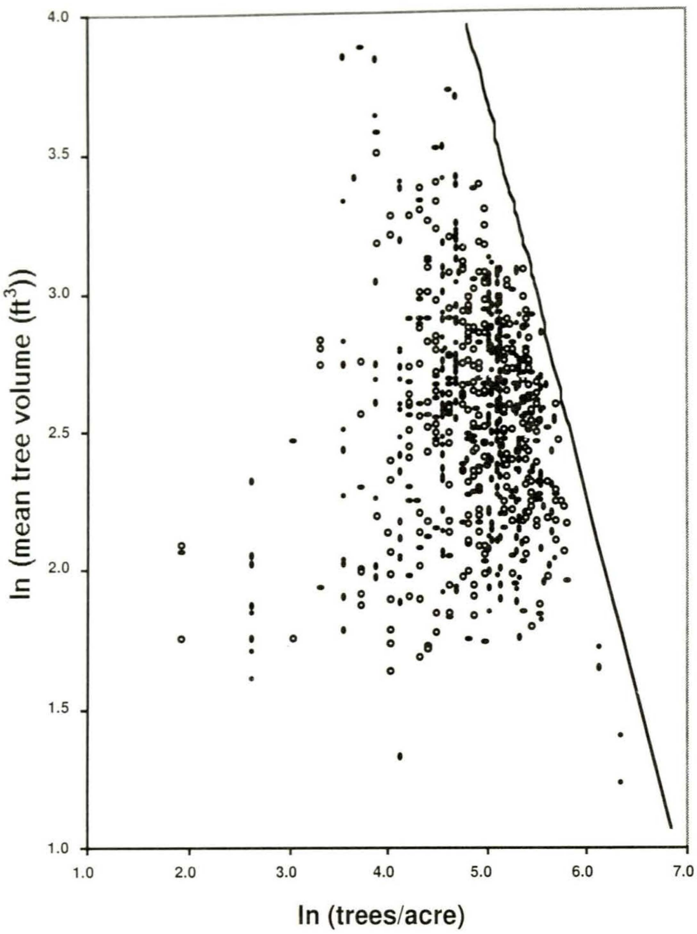


Figure 1.—*The maximum size-density relationship, ln (Mean Tree Volume (ft^3)) = 10.86 - 1.43 *ln (Trees Per Acre), for the sugar maple - ash ecological type.*

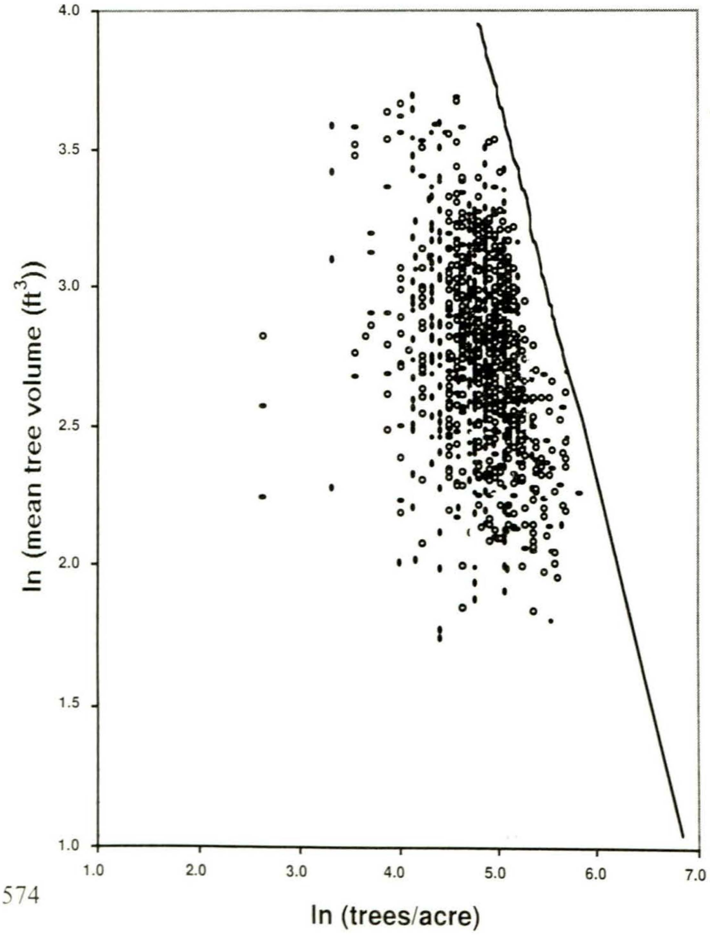


Figure 2.—*The maximum size-density relationship, ln (Mean Tree Volume (ft^3)) = 10.86 - 1.43 *ln (Trees Per Acre), for the beech – red maple ecological type.*

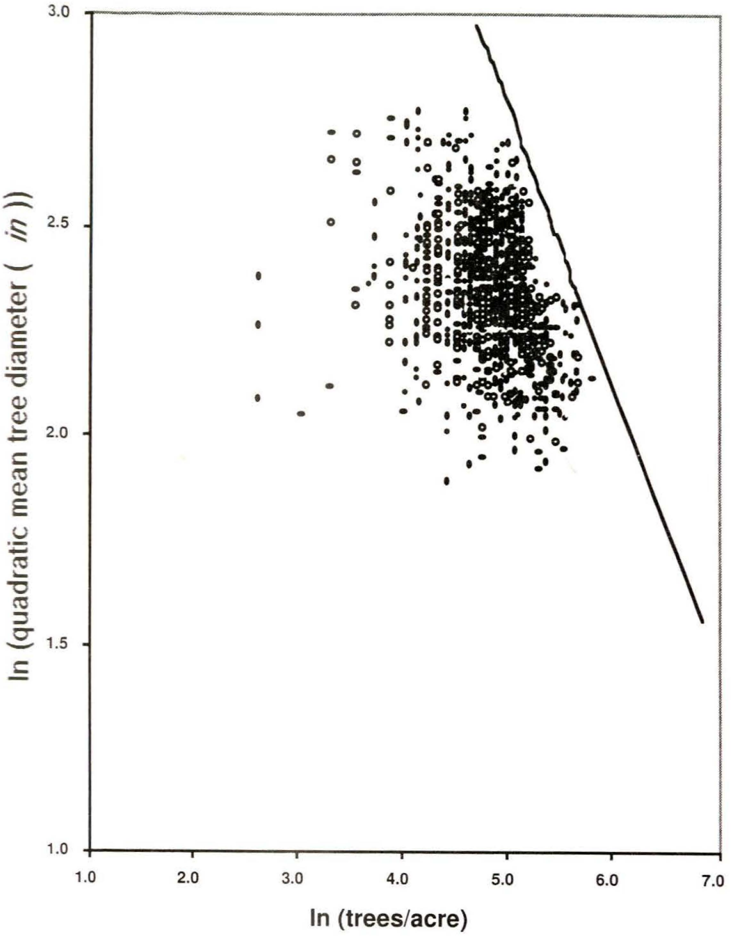


Figure 3.—*The maximum size-density relationship, ln (Quadratic Mean Tree Diameter (in)) = 6.08 - 0.66 * ln (Trees Per Acre), for the sugar maple – ash ecological type.*

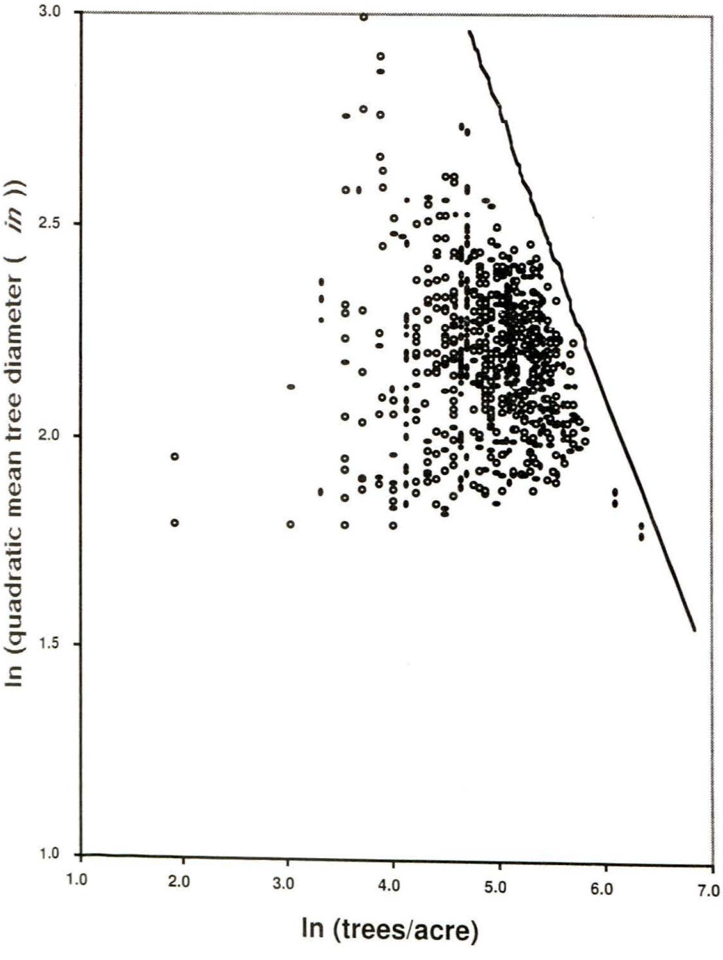


Figure 4.—*The maximum size-density relationship, ln (Quadratic Mean Tree Diameter (in)) = 6.08 - 0.66 * ln (Trees Per Acre), for the beech – red maple ecological type.*

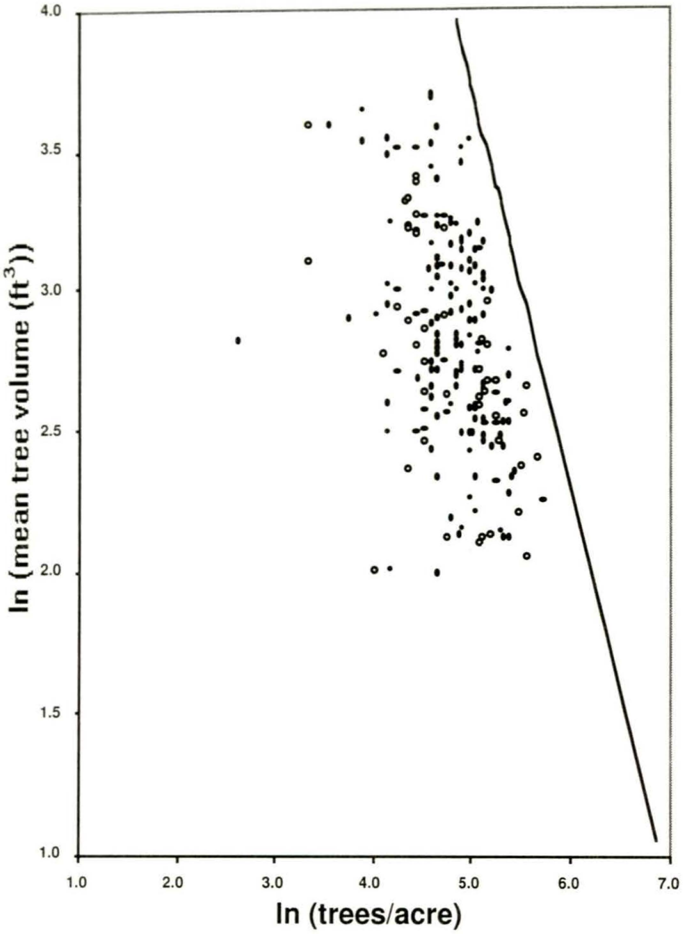


Figure 5.—*The maximum size-density relationship, ln (Mean Tree Volume (ft^3)) - ln (Trees Per Acre), for stands having > 70 percent square feet of basal area in sugar maple.*

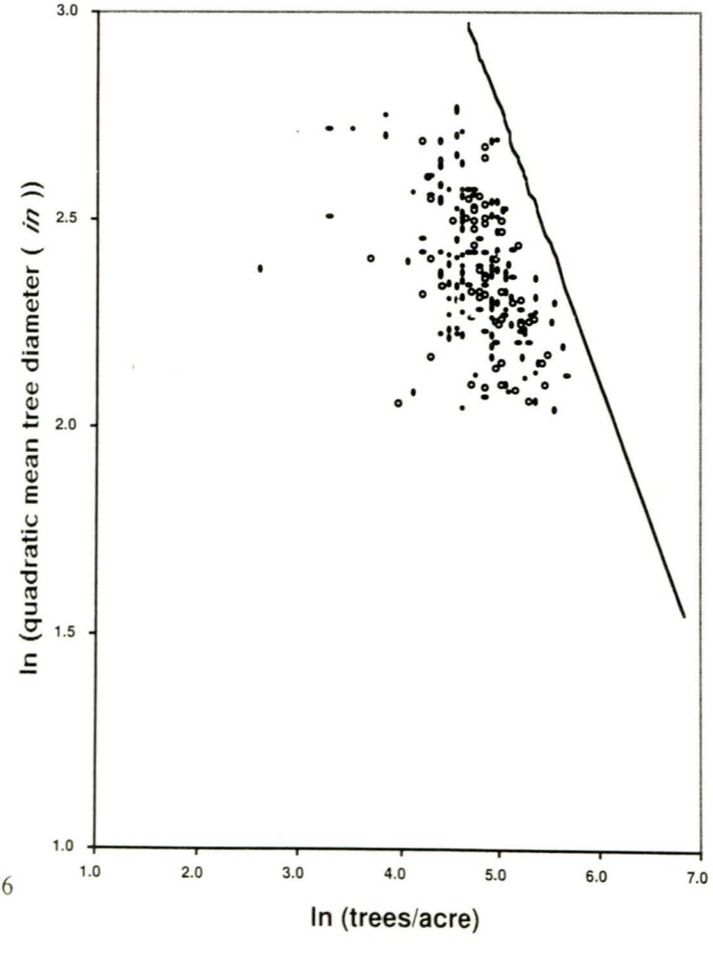


Figure 6.—*The maximum size-density relationship, ln (Quadratic Mean Tree Diameter (in)) – ln (Trees Per Acre), for stands having > 70 percent square feet of basal area in sugar maple.*

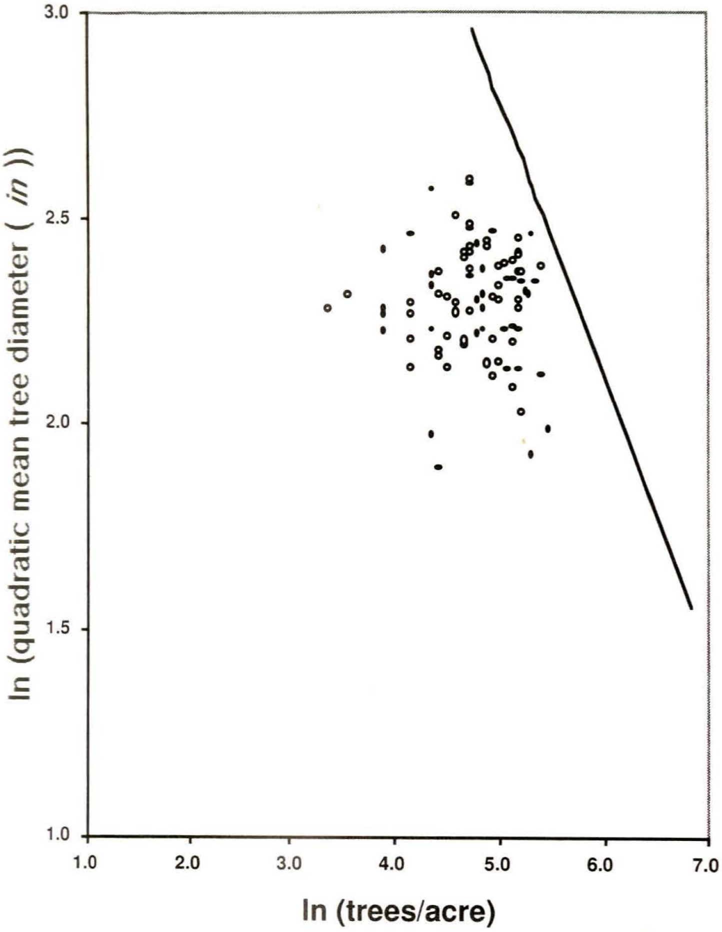


Figure 7.—*The maximum size-density relationship, ln (Quadratic Mean Tree Diameter (in)) – ln (Trees Per Acre), for stands having > 70 percent square feet of basal area in beech.*

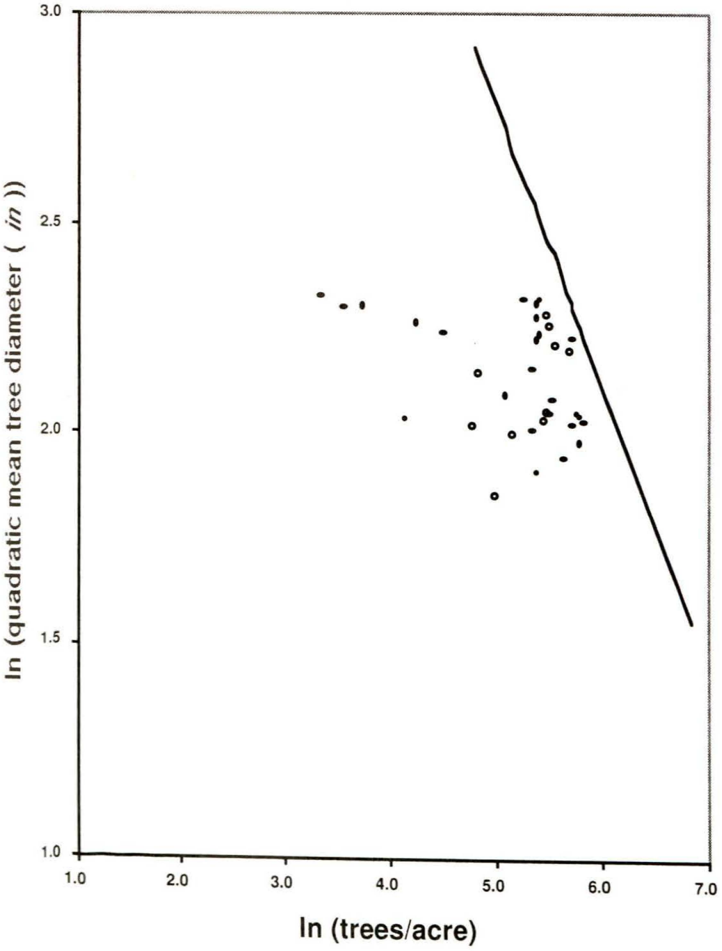


Figure 8.—*The maximum size-density relationship, ln (Quadratic Mean Tree Diameter (in)) – ln (Trees Per Acre), for stands having > 70 percent square feet of basal area in red maple.*

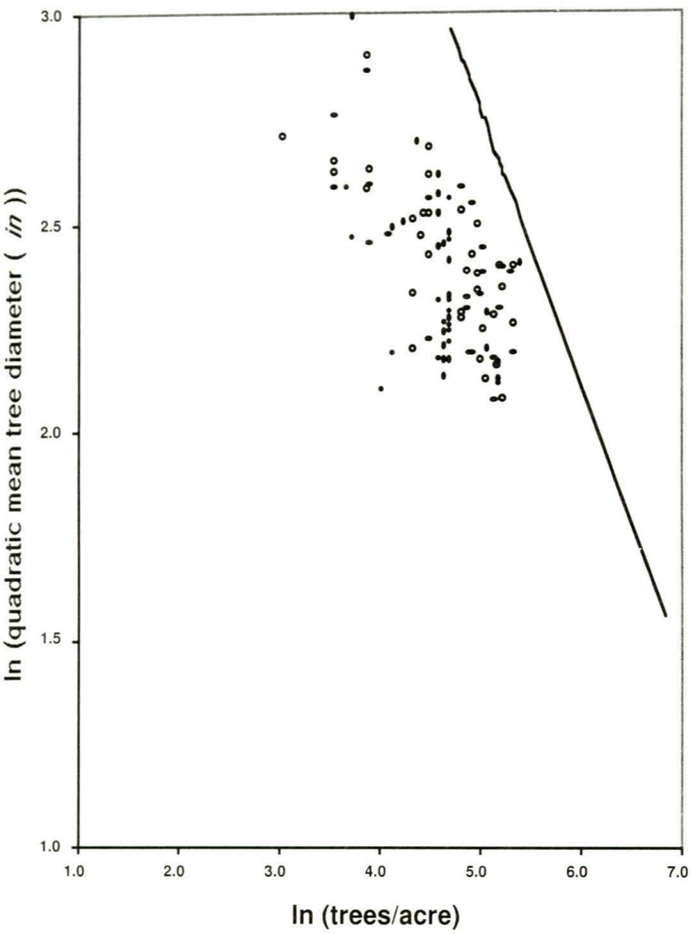


Figure 9.—*The maximum size-density relationship, ln (Quadratic Mean Tree Diameter (in)) – ln (Trees Per Acre), for stands having > 70 percent square feet of basal area in yellow birch.*

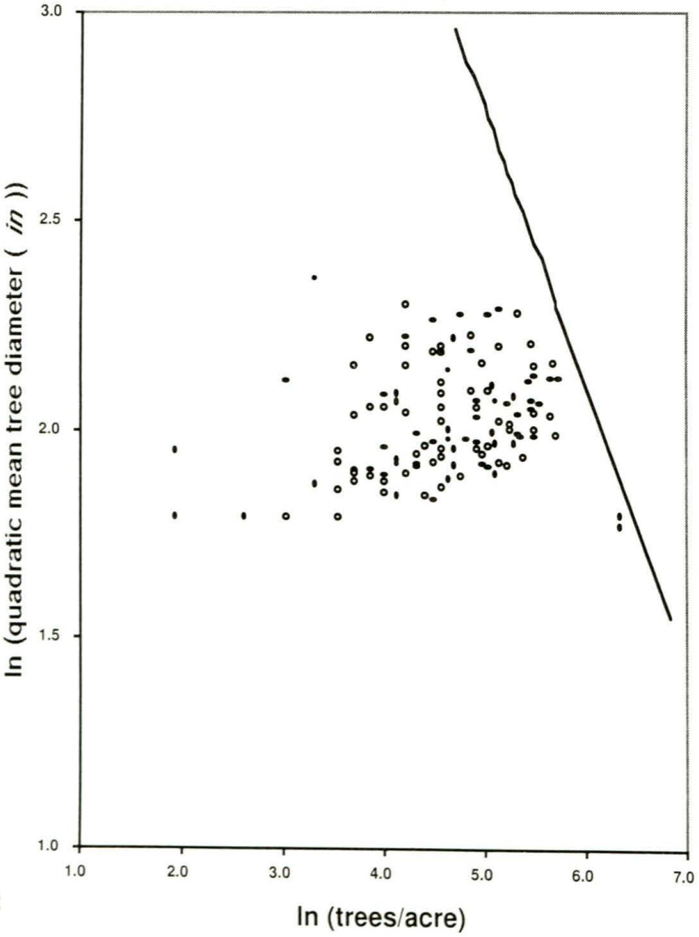


Figure 10.—*The maximum size-density relationship, ln (Quadratic Mean Tree Diameter (in)) – ln (Trees Per Acre), for stands having > 70 percent square feet of basal area in paper birch and aspen plots combined.*

Gingrich, S.F. 1967. Measuring and evaluating stocking and stand density in Upland hardwood forest in the Central States. Forest Science. 13: 38-53.

Hayes, J.P.; Chan, S.S.; Emmingham, W.H.; Tappeiner, J.C.; Kellogg, L.D.; Bailey, J.D. 1997. Wildlife response to thinning young forests in the Pacific Northwest. Journal of Forestry. 95: 28-33.

Jack, S.B.; Long, J.N. 1996. Linkages between silviculture and ecology: an analysis of density management diagrams. Forest Ecology and Management. 86: 205-220.

Kershaw, J.A.; Fischer, B.C. 1991. A stand density management diagram for sawtimber-sized mixed upland Central hardwoods. In: Proceedings of 8th Central hardwood forest conference; 1991 March 4-6; University Park, PA. Gen. Tech. Rep. NE-148. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station: 414-428.

Leduc, D.J. 1987. A comparative analysis of the reduced major axis technique of fitting lines to bivariate data. Canadian Journal of Forest Research. 17: 654-659.

Lilieholm, R.J.; Kessler, W.B.; Merrill, K. 1993. Stand density index applied to timber and goshawk habitat objectives in Douglas-fir. Environment Management. 17: 773-779.

Newton, P.F. 1997. Algorithmic version of black spruce stand density management diagrams. Forestry Chronicle. 73: 257-265.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research. 46(7): 627-638.

Solomon, D.S.; Leak, W.B. 1969. Stocking, growth and yield of birch stands. In: Proceedings of the Birch Symposium; 1969 August 19-21; University of New Hampshire, Durham, NH. Northeastern Forest Experiment Station: 106-118.

Solomon, D.S.; Leak, W.B. 1986. Simulated yields for managed Northern hardwood stands. Res. Pap. NE-578. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Research Station.

Solomon, D.S.; Herman, D.A.; Leak, W.B. 1995. FIBER 3.0: an ecological growth model for Northeastern forest types. Gen. Tech. Rep. NE-204. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Zeide, B. 1987. Analysis of the 3/2 power law of self-thinning. Forest Science. 33: 517-537.

Adaptation of FIBER for Forest Inventory and Analysis Growth Projections in the State of Maine

Dale S. Solomon, Thomas B. Brann, and Lawrence E. Caldwell

Abstract.—The model FIBER (Forest Increment Based on Ecological Rationale) was selected by the Technical Review Team on the Sustainability of Timber Supplies in the State of Maine to construct yield information using USDA Forest Service Forest Inventory and Analysis (FIA) field data. FIBER habitat criteria based on soil characteristics, species composition of overstory, and adjusted understory trees were used to classify FIA plots compared to the past and present records of the FIA inventory forest typing. Yield curves based on ecological classification and species compositional succession were constructed for input into the model ATLAS (Aggregate Timberland Assessment).

Scientifically based practices are critical and a required component of forest policy for the State of Maine. Sustaining a viable forest is economically essential to address the recreational needs and provide for an adequate timber industry supply. Thus, policy makers are required to consider levels of timber harvest that are sustainable, both biologically and economically. The use of regional planning and policy application models is one method of combining structure and regulation to ensure continuance of the "Maine Woods" for future generations to enjoy. Cooperation between the Maine State Forest Service and the U.S. Department of Agriculture (USDA), Forest Service, Northeastern Research Station has initiated a statewide study using Forest Inventory and Analysis (FIA) inventory plot data to assess present and future forest conditions in developing policy recommendations for the State of Maine. A technical review team, comprised of scientists and individuals from industry, the Forest Service, universities, and public interest groups, has chosen the FIBER 3.0 model (Forest Increment Based on Ecological Rationale) (Solomon *et al.* 1995) to grow the mixed species stands and generate yield curves based on six ecological classifications using the FIA plots.

The construction of the FIBER model (Solomon *et al.* 1986) is based on a regional database across northern New York and New England to Nova Scotia. The two-stage matrix model structure captures the changes in different species growth rates and species succession for different ecological classifications that occurs during stand maturation. These classes are indicative of the *probable* climax or late succession overstory species composition, which is theoretically determined by a set of biophysical relationships (Leak 1982). This classification is analogous to natural habitats that state the predominant overstory/understory of *potential* climax vegetation originating in the western United States (Daubenmire 1952, Pfsister and Arno 1980). By growing plot level data in FIBER to stratify all timberlands into the six ecological types, an ecologically based timber supplies projection can be produced.

The 1995 FIA survey for Maine utilized a sample of 2,698 plots and subplots inventorying roughly 17 million acres of timberland in the state. The forest types and forest-type groups from the FIA inventories are not directly comparable with the ecological classification in FIBER. Therefore, the FIA forest types were placed into FIBER classes for analysis. Table 1 shows that from the three different inventories, the acreage in each forest type changed over time. The USDA Forest Service defines forest type as "a classification of forest land based on the species that form a plurality of live-tree basal-area stocking" (Griffith and Alerich 1996). The forest types of Maine's woods, and even the algorithms used to define them, have changed rather significantly over the last 4 decades (Powell and Dickson 1984). These species changes, softwoods decreasing and hardwoods increasing, are due to both natural processes and human disturbance. Therefore, the FIA plots need to be reclassified into the most appropriate FIBER habitats.

This paper is a preliminary overview of the process used to adapt the ecological model FIBER and FIA forest types to produce realistic growth and yield curves. These yield curves, by ecological habitats, were input for the ATLAS (Aggregate Timberland Assessment) projection model (Mills and Kincaid 1992) to match timber supply with timber demand.

Project Leader, USDA Forest Service, Northeastern Research Station, Durham, NH 03824, USA; Professor, Department of Forest Management, University of Maine, Orono, ME 04469, USA; and Maine Forest Service, Augusta, ME 04333, USA, respectively.

Table 1.—*FIBER habitat compared with FIA forest type by timberland area for 1971, 1982, and 1995*

FIBER habitat	Forest type	Forest Inventory and Analysis 1971	1982	1995
		- - - - *Million acres*		- - - -
Sugar maple/ Ash	Sugar maple/beech/yellow birch	3.1	3.1	3.9
	Black cherry	—	—	.1
		(3.1)[1]	**(3.1)**	**(4.0)**
Beech/Red Maple	Red maple/northern hardwoods	1.2	1.2	1.5
	Pin cherry	—	.1	.1
	Mixed northern hardwoods	.6	.5	.8
		(1.8)	**(1.8)**	**(2.4)**
Oak/ White pine	Oak/pine	—	—	.5
	Oak/hickory	.3	.4	.3
	Pine/hemlock	1.4	1.6	.7
		(1.7)	**(2.0)**	**(1.5)**
Cedar/ Black spruce	Tamarack	.1	.1	.1
	N. white cedar	1.4	1.6	1.3
	Black spruce	.2	.3	.2
	Elm/ash/red maple	.3	.2	.4
		(2.0)	**(2.2)**	**(2.0)**
Spruce/fir	Balsam fir	1.7	1.1	1.8
	Red spruce	1.1	1.2	.9
	Spruce/fir	3.7	3.3	1.5
	White spruce	.2	.2	.2
	Aspen/birch	1.0	1.5	2.2
		(7.7)	**(7.3)**	**(6.6)**
Hemlock/red spruce	Hemlock	.5	.6	.5
		(.5)	**(.6)**	**(.5)**
	TOTAL	**16.8**	**17.0**	**17.0**

[1] Values in parentheses are subtotals.

METHODS AND RESULTS

The 1995 FIA database contains 183 variables including past (1982 inventory) and current tree list information as well as regeneration data tallied in the 1995 remeasurement. To analyze 2,698 stands, modifications to FIBER 3.0 and to the FIA forest typing of inventory plots were required in a flexible inventory program since FIBER 3.0 is designed as a single-stand analytical tool. Therefore, FlexFIBER 4.xx (Brann and Solomon unpublished) was developed to handle batch processing of stands by ecological habitats to produce yield data files for ATLAS. We ran all 2,698 timberland plots through the FlexFIBER model to generate independent overstory habitat assignments.

The habitat algorithm in FIBER 3.0 looks at the percentages of the basal area by tree species in the existing forest stand that, through an association to different soil characteristics, are indicative of successional trends. An initial assignment by FIBER led to a different distribution of FIA timberland acres in table 2, acknowledging that 135 plots had less than 5 square feet of basal area required by the model and therefore were not included in this first phase distribution of acreage.

Table 2.—*Phase I classification of 1995 Forest Inventory and Analysis timberland acreage into six FIBER ecological habitats*

Ecological habitat	Acres	Acres	Hardwood basal area
		- - - *Percent* - - -	
Beech/Red Maple	2,367,769	14.6	91
Cedar/Black Spruce	2,851,104	17.6	19
Hemlock/Red Spruce	1,629,054	10.0	34
Oak/White Pine	2,248,710	13.9	47
Spruce/Fir	5,188,685	32.0	36
Sugar Maple/Ash	1,930,294	11.9	92

The model was further adapted in FlexFIBER 4.xx to consider understory tree species composition. The understory trees (<4.5 inches) on a plot are normally not considered as an input to the FIBER 3.0 model. The FIA data contained understory species information, and an assignment of ingrowth species into each ecological habitat was made. Profile, by habitats, of all 2,698 timberland plots were sorted by FIBER using the number of trees by species per acre in the understory in addition to the past FIA forest type classification. This adjustment allows for a more accurate description of ingrowth, which might have been overlooked using only the overstory stand. This was particularly important as a means of accurately following species succession in spruce/fir habitats, which currently have a high level of red maple (*Acer rubrum L.*), aspen (*Populus spp.*), and northern white cedar (*Thuja occidentalis L.*) stocking.

Plots were then divided into three groups for each of the six ecological classifications. To address the differences between the overstory and understory assigned by the FIBER model, the groups were classified as plots that had: a) agreement between the understory and overstory (1,201 plots); b) different understory and overstory assignments (1,362 plots); and c) no overstory and did not fall into the above two groups (135 plots).

After looking through the 1,201 plots that had agreement between overstory and understory, we felt that the data describing these plots provided few opportunities to improve this subset. So instead, we focused on plots with disagreement between the overstory/understory and plots with no overstory recorded.

In a two-step process, 1,497 (1,362 + 135) plots were considered for habitat reassignment. In the first step, we grouped the different overstory and understory by FIBER habitat classifications. Then, using a list of 12 plot-level variables of current and past FIA forest types, soil-based habitat information, parent material, moisture class, elevation, measures of volume, and species composition, plots were classified (table 3). The sorted plots by FIBER habitat and past FIA forest type, within a given FIBER habitat, could be profiled while also allowing plots with like variables to be listed together. Of the 1,362 plots scrutinized, 823 remained in the initial FIBER habitat classification. This process allowed for different species and different growth rates of the same species to aggregate on plots where regeneration was not the same species composition as the existing stand overstory. Spruce-fir habitats that are heavily harvested usually regenerate to hardwoods; however, the plots should not be classified as hardwood habitat but as spruce-fir, since species succession will return the stand to spruce-fir composition over time. After examining the remaining plot variables over time and the tree list data, it became apparent that some general guides could be developed to move groups of plots with similar characteristics into more appropriate FIBER habitat classifications, especially since the model FIBER follows species succession during stand maturation. For example, it seemed that many quality sites, Sugar Maple/Ash plots (past FIA type of Maple-Beech-Birch, mesic soils, Sugar Maple/Ash understory) did not have the basal area requirements for Sugar Maple/Ash habitat. While somewhat subjective, we recognized the persistence of a Sugar Maple/Ash understory on mesic soils, as well as the homogeneity of many of the plots, and reassignment was made to Sugar Maple/Ash. Fundamental understanding of existing timber types and reflection on the actual plot data and species changes over time became the basis for the development of guides for placing plots into habitat classification when the plot overstory and understory do not agree. The following guides and guides in table 3 were applied to the understory classification that resulted in changing the remaining 539 plots. Within a FIBER type, these rules were intended to be hierarchical. In application, however, there were few, if any, cases where these guides were in conflict.

Table 3.—*Forest Inventory and Analysis plot level variables used in the reclassification of FIA forest types into FIBER habitats*

Overstory habitat	Plot ID	FIBER understory	Current FIA type	Past FIA type	Soil-based habitat	Parent[1] material	Moisture[2] class	Elevation	BioPhysical	Total net volume	AGS[3]	Hardwood	2 Story stands
								Meters		*ft³*	*Percent*	*Percent*	
BE/RM	17-307-1	SF	Aspen	Aspen		3	4	275	Western Mountains	2114	87.0	13.0	0
	3-262-1	SF	SM/BE/Birch	Aspen	SM/ASH	2	3	220	Aroostook Lowland	651	100.0		0
	9-195-1	SF	RM/Northern Hardwoods	Balsam Fir		4	4	50	East Coastal Region	995	100.0	0.0	0
CE/BS	3-274-1	BE/RM	Black Spruce	Black Spruce	CE/BS	6	5	185	Aroostook Lowland	2830	96.3	3.7	0
	27-126-1	BE/RM	SM/BE/Birch	Hemlock	SM/ASH	1	3	145	Central Interior	770	97.8	2.2	0
	25-684-1	BE/RM	Northern White Cedar	Northern White Cedar	CE/BS	6	5	150	Western Foothills	1161	60.8	39.2	0
OAK/WP	17-314-1	BE/RM	Northern Red Oak	Northern Red Oak	OAK/WP	2	2	170	Southwest Interior	537	89.3	10.7	0
	13-96-1	BE/RM	White Pine/ Hemlock	White Pine	OAK/WP	3	2	80	Central Interior	1492	97.9	2.1	0
SPRUCE/ FIR	25-740-1	BE/RM	Red Spruce	*Unrecorded*	SP/FIR	4	4	370	Aroostook Hills	2900	98.4	1.6	0
	29-15-1	BE/RM	RM/Northern Hardwoods	Balsam Fir	BE/RM	2	3	70	Eastern Lowlands	644	73.2	26.8	0
SM/ASH	3-68-1	BE/RM	SM/BE/Birch	Mixed Northern Hardwood	SM/ASH	1	3	400	Aroostook Hills	1598	100.0	0.0	0
	17-5-1	BE/RM	SM/BE/Birch	SM/BE/Birch	SM/ASH	2	3	185	Western Mountains	2077	98.3	1.7	0

[1] Parent material: 1 = compact till; 2 = loose till; 3 = sand and gravel; 4 = silt and clay; 5 = alluvium; 6 = organic

[2] Moisture class: 1 = very dry; 2 = dry; 3 = mesic; 4 = wet; 5 = very wet

[3] AGS = Acceptable Growing Stock

Guides Used to Supplement Assignment of Fiber Habitat Classification for Plots with Disagreement Between Overstory and Understory Species Composition.

SUGAR MAPLE—ASH HABITAT:

Plots with Sugar Maple—Ash FIBER understory and Sugar Maple—Ash soil were placed in Sugar Maple—Ash habitat. This applies across all FIBER habitats, and supersedes other guides (changes 82 plots).

BEECH—RED MAPLE HABITAT:

1. Plots with Spruce—Fir FIBER understory and a fir, red-white spruce, or cedar past FIA type were placed in Spruce—Fir habitat (changes 35 plots).
2. Plots with Spruce—Fir FIBER understory and an intolerant hardwood past FIA type (aspen, paper birch) were placed in Spruce—Fir habitat. If the past FIA type is unrecorded, the current FIA type can be substituted (changes 44 plots).

CEDAR—BLACK SPRUCE HABITAT:

1. Plots with red-jack-pitch pine FIA type were placed in Oak—White Pine. This is due to FIBER soil and site categories of these pines and having growth rates similar to tamarack (changes 7 plots).
2. Plots with Spruce—Fir FIBER understory and fir, red-white spruce past FIA type were placed in Spruce—Fir habitat. If past FIA type is unrecorded, current FIA type can be substituted (changes 144 plots).
3. Plots with hardwood FIBER understory (Beech—Red Maple, Sugar Maple—Ash) and tolerant hardwoods for both FIA types were placed in Beech—Red Maple habitat (changes 3 plots).
4. Plots with Hemlock—Red Spruce FIBER understory and hemlock or red spruce FIA types were placed in Hemlock—Red Spruce habitat (changes 3 plots).
5. Plots with Spruce—Fir FIBER understory and an FIA type other than cedar, black spruce, or tamarack were placed in Spruce—Fir habitat, unless soils are Cedar—Black Spruce. If soils are Cedar—Black Spruce, then no change (changes 42 plots).

HEMLOCK—RED SPRUCE HABITAT:

1. Plots with Sugar Maple—Ash soils and past FIA type of any northern hardwoods were placed in Beech—Red Maple habitat. Current FIA type can be substituted if past FIA type is not available. Plots with Sugar Maple—Ash soils and Sugar Maple—Ash FIBER understory have already been assigned Sugar Maple—Ash (changes 29 plots).
2. Plots with Beech—Red Maple or Sugar Maple—Ash FIBER understory and FIA types of any northern hardwoods (or current if past is unrecorded) were placed in Beech—Red Maple habitat (changes 16 plots).

OAK—WHITE PINE HABITAT:

1. Plots with Hemlock—Red Spruce FIBER understory and a hemlock or red spruce past FIA type (or current if past is unrecorded) were placed in Hemlock—Red Spruce habitat (changes 10 plots).
2. Plots with Sugar Maple—Ash soil and "non-Oak" for both FIA hardwood types were placed in Beech—Red Maple habitat (changes 21 plots).
3. Plots with Beech—Red Maple FIBER understory and "non-Oak" for both FIA hardwood types were placed in Beech—Red Maple habitat (changes 21 plots).

SPRUCE—FIR HABITAT:

1. Plots with Beech—Red Maple or Sugar Maple—Ash FIBER understory, and both FIA hardwood types (can substitute current FIA type if past is unrecorded) were placed in Beech—Red Maple habitat (changes 61 plots).
2. Plots with Sugar Maple—Ash soils and both FIA hardwood types were placed in Beech—Red Maple habitat (changes 16 plots).

Also, in this second phase, the assignment of the 135 plots was made using the same 12 plot descriptor variables and tree list data. However, plots were placed individually in habitats without guides being explicitly stated. Because of the absence of an overstory, the FIBER understory from the initial run, soil, and the past forest type were utilized to assign habitat. The Phase II assignment, while different from the FIA typing and initial FIBER assignment, produced an objective refinement of the distribution of the total timberland acres as listed in table 4.

The staff conducted a third phase at a higher level of resolution to correct plots they felt either were not or could not be captured correctly by Phase I or II. The same 12 variables scrutinized in earlier assessments, supplemented by subjective criteria of the tree list

Table 4.—*Phase II Reclassification of 1995 Forest Inventory and Analysis timberland acreage into six FIBER ecological habitats using overstory and understory trees*

Ecological habitat	Acres	Acres	Hardwood basal area
		Percent	*Percent*
Beech/Red Maple	2,876,515	17.0	77
Cedar/Black Spruce	1,599,084	9.4	15
Hemlock/Red Spruce	1,447,076	8.5	30
Oak/White Pine	1,928,361	11.4	43
Spruce/Fir	6,599,835	38.9	36
Sugar Maple/Ash	2,501,361	14.8	87

inspections of the FIA data, were used to distribute timberland acreage (table 5). This distribution reflects a higher percentage of Spruce/Fir, Sugar Maple/Ash, and Beech/Red Maple acres than the initial FIBER or Phase II assignments. Also, lower percentages of Cedar/Black Spruce, Hemlock/Red Spruce, and Oak/White Pine acres were the result of moving the less than obvious plot assignments into the other three habitats. FIBER was then used to estimate yields by management units and intensities and was used in the ATLAS timber supply analysis.

Attempting to understand the accuracy of our current distribution, it is helpful to look at past FIA inventories for Maine in the 1950's, 1960's, and 1970's. Catastrophic attacks by the spruce budworm in 1970-80 caused excessive mortality (Solomon and Brann 1992). Salvage of that mortality and excessive harvesting to prevent windthrow changed species compositions and ground cover types for future FIA inventories. For this reason, the current forest habitat classification is confounded, and data from earlier inventories must be incorporated to follow the species' successional trends over time. For example, the 1959 FIA inventory (Ferguson and Longwood 1960) recorded 8.4 million acres of spruce-fir type group as compared to the 1995 FIA inventory of 6 million acres. Although the FIA forest typing algorithms have changed since 1959, it is safe to say that harvest activity over the past 3 decades has promoted a higher level of stocking in both hardwoods and northern white cedar, while decreasing plots stocked with spruce and fir. However, many of these stands have a strong component of spruce and fir in the understory and, in many cases, reflect the successional tendency of these sites. Our approach uses the convenience of FIBER's batch level processing with the valuable understory, ecological, and forest type information from FIA to follow forest tree species growth and succession through time.

CONCLUSION

With Maine's timberland acres aggregated into these six ecological types, yield curves based on a variety of harvesting intensities and silvicultural regimes within different management units were constructed. FIBER was used to project the FIA inventory timberland plots data (except the 135 without an overstory). FIBER produced updated inventory estimates every 5 years and constructed a time series file of the projected inventory. The time series files were used to develop yield tables by the above ecological habitats and volume classes for ATLAS. In using the FIBER ecological habitats as a stratification, the

Table 5.—*Final distribution of 1995 Forest Inventory and Analysis timberland acreage by ecological habitat as adjusted and supplemented by tree list inspections*

Ecological habitat	Acres	Acres	Hardwood basal area
		Percent	*Percent*
Beech/Red Maple	3,187,980	18.8	73
Cedar/Black Spruce	1,612,559	9.5	14
Hemlock/Red Spruce	1,290,525	7.6	31
Oak/White Pine	1,290,311	7.6	42
Spruce/Fir	6,909,619	40.8	35
Sugar Maple/Ash	2,661,238	15.7	86

ATLAS model results extend beyond current species inventoried, while allowing the consequences of alternative silvicultural regimes and stand maturation to be modeled. Classification of FIA plots into a FIBER habitat during the field data collection would improve future processing. Phase I and II are within different management units being incorporated into FlexFIBER 4.xx for application in Maine, New Hampshire, New York, and Vermont.

ACKNOWLEDGMENTS

We would like to thank Dr. Lianjun Zhang, State University of New York ESF and Mr. William B. Leak, USDA Forest Service, Northeastern Research Station, for their critical review of this manuscript.

LITERATURE CITED

Brann and Solomon (unpublished). Application guide for the adaptation of FIBER for growth projections.

Daubenmire, R. 1952. Forest vegetation of northern Idaho and adjacent Washington, and its bearing on concepts of vegetation classification. Ecology Monograph. 22: 301-330.

Ferguson, R.H.; Longwood, F.R. 1960. The timber resources of Maine. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 77 p.

Griffith, D.M.; Alerich, C.L. 1996. Forest statistics for Maine, 1995. Resour. Bull. NE-135. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. p. 13.

Leak, W.B. 1982. Habitat mapping and interpretation in New England. Res. Pap. NE-496. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 28 p.

Mills, J.R.; Kincaid, J.C. 1992. The aggregate timberland assessment system – ATLAS: a comprehensive timberland projection model. Gen. Tech. Rep. PNW-218. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 16 p.

Pfsister, R.D.; Arno, S.F. 1980. Classifying forest habitat types based on potential climax vegetation. Forest Science. 26(1): 52-70.

Powell, D.S.; Dickson, D.R. 1984. Forest statistics for Maine 1971 and 1982. Resour. Bull. NE-81. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 10-11.

Solomon, D.S.; Brann, T.B. 1992. Ten-year impact of spruce budworm on spruce-fir forests of Maine. Gen. Tech. Rep. NE-165. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 44 p.

Solomon, D.S.; Herman, D.A.; Leak, W.B. 1995. FIBER 3.0: an ecological growth model for northeastern forest types. Gen. Tech. Rep. NE-204. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Solomon, D.S.; Hosmer, R.A.; Hayslett, H.T., Jr. 1986. A two-stage matrix model for predicting growth of forest stands in the Northeast. Canadian Journal of Forest Research. 16: 521-528.

Inventory Implications of Using Sampling Variances in Estimation of Growth Model Coefficients

Albert R. Stage and William R. Wykoff

Abstract.—Variables based on stand densities or stocking have sampling errors that depend on the relation of tree size to plot size and on the spatial structure of the population. Ignoring the sampling errors of such variables, which include most measures of competition used in both distance-dependent and distance-independent growth models, can bias the predictions obtained from regression analysis.

The bias occurs if the sampling errors differ between the calibration data and the prediction data. Differences arise from several sources. For example, plot designs often differ between two major applications of growth models: updating inventory statistics, and simulating effects of proposed management actions. Even in a single analysis, not all data come from the same plot size, especially if plot designs vary by diameter classes. In addition, in growth modeling, plot-size to tree-size relations change as the trees grow and management modifies spatial structure. However, if the sampling errors of the variables are used in estimating model coefficients, and again when the model is applied, the same model can be used with different plot designs. Local variation in stocking can be measured by individual subplots in the context of a distibution of plots within the stand. When imbedded in a (semi-) distance-independent, individual-tree model for stand development, the Structural-Based-Prediction method increases model sensitivity to competition compared to ordinary least squares estimates. This model has particular application to spatially irregular or patchy stands.

Models of many ecological processes depend on variables that are defined by spacing, density, and size of individual trees or of aggregates of trees at a location. Examples range from the size of big-game home-ranges (Pauley *et al*. 1993) to estimates of sediment deposition (Elliot and Hall 1997), from estimates of Net Primary Productivity to detailed models of stand development, and you can supply many more. Once developed, application of these models by resource analysts requires inventory data to provide initial values of density and stocking. Unfortunately, both modelers and inventory analysts usually overlook the effects on their analysis of predictor variables that are sample-based, and hence include a random error. Ignoring the error can lead to underestimating the significance of variables and to biases in the predictions (Fuller 1987, Jaakkola 1967).

Although statistical solutions for errors-in-variables problems have been finding their way into forestry applications (Goelz and Burk 1996, Kangas 1998, Lappi 1991), Stage and Wykoff (1993, 1998) appear to be the first to directly solve the problem posed by sampling errors of the competition variables in growth models.

We address two sources of sampling error in competition variables—within a single plot or subplot, and between the several subplots that may be used to characterize the spatial variation within the stand or inventory cluster.

Figure 1 illustrates the sampling error in just the tree density component of competition as measured on a single plot applicable to a single subject tree. Here, the sampling variance of density about the subject tree is the variance among all possible random sampling points that would include the subject tree. This variation depends on the size and shape of plot and on the spatial arrangement of the trees. For stocking measures such as basal area per unit of land area, tree size distribution is a component of the variation. Tree-centered measures of competition are also subject to sampling variation, although from different sources (Schreuder and Williams 1995).

The within-plot source of variation is seldom measured, so we estimate it from a model of spatial variation. The second source of variation—between the subplots within an inventory cluster at a location or within a stand examination—is readily computed from the inventory data. However, if the inventory measures only a single plot at each location, the same variance model used for the within-plot variation can be invoked.

Principal Mensurationist (retired) and Research Forester, respectively, USDA Forest Service, Intermountain Research Station, Forestry Sciences Laboratory, 1221 S. Main Street, Moscow, ID 83843, USA; (208) 883-2345; FAX: (208) 883-2318; astage@moscow.com; wykoff@moscow.com.

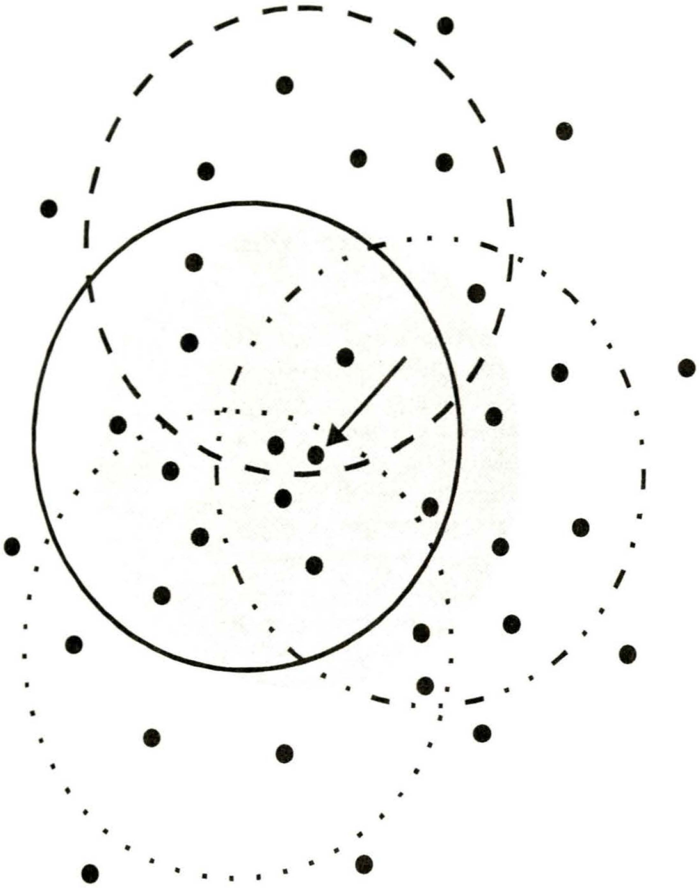


Figure 1.—*Shaded area covers possible locations of sampling points about which a circular plot would include the subject tree indicated by the arrow. Four of these possible plot locations are shown, with the varying number of trees to be tallied in each.*

INTRODUCING GROWTH MODELS TO SAMPLING ERROR

Models based on ordinary least squares estimation using inventory data can avoid the bias part of the problem if they are, in turn, applied to inventory data having the same error properties (Stage 1977). This criterion is violated when plot sizes (or number of plots per stand) differ between the calibration data set and the application data set. It is further violated in iterations of growth models beyond the first cycle of prediction if plots of differing sizes are used to sample different size classes of trees. During a projection, tree sizes change, but plot size is fixed at the time of the inventory. Likewise, outputs from growth models used as input to models of other ecosystem components are vulnerable to the same problems.

Our solution to the problem of using different plot sizes and numbers of subplots per stand or location has three steps:

1. Estimate the sampling errors applicable to the calibration data set. Depending on the definition of the competition variables, this variance may depend on the standard error of the mean between subplots. If the competition variable is defined separately for each subplot, develop a model of the variance within the subplot.

2. Subtract the sampling error covariances characterizing the calibration data set from the covariances of the observed variables. Save the coefficients of this structural model and relevant parts of the inverse of its covariance matrix to be used at prediction time.

3. When calculating predictions, the error covariances applicable to the new data set are added to the reduced covariance matrix from step 2. The result is a new covariance matrix of "observed" variables. From its inverse and the coefficients of the structural model, new coefficients are calculated for prediction. Fortunately, there are useful shortcuts to the matrix algebra that cut this task to a reasonable size. (This step is the major difference between our procedure and the one used by Kangas (1998)). We have called this three-step procedure "Structural Based Prediction" (SBP).

Admirers of Robert Service may have the sense that this procedure bears certain similarities to Chewed-Ear Jenkins' solution to the syndicate holding bets on the outcome of his hair restoring efforts. While his wife poured on the hair-restoring elixir, Chewed-Ear secretly shaved off the fuzz. However, we show that effects can be substantial when either plot configurations differ, or when management action such as thinning changes the variation within or between plots.

APPLYING SBP IN A SEMI-DISTANCE-INDEPENDENT MODEL OF FOREST GROWTH

The model we developed was motivated by the need to provide a predictive model of stand development with explicit representation of within-stand (or within-location) variation in stocking. In particular, we wanted a model that could represent stocking variation at a broader scale than seems feasible with distance-dependent formulations. Therefore, the model was designed to be used either with a stand examination consisting of a scatter of subplots through the delineated stand or with an inventory of clusters of subplots. An inventory in which the cluster is reduced to a single plot at widely scattered locations is just a special case, for which the model could be used with some loss of resolution.

Competition Measures

To meet our objective of increasing sensitivity to spatial variation, we provided for two scales of competition effects: effects dependent on the local intensity of stocking as measured by a single, rather small plot; and effects that depend on the general context of stocking in which the plot is located.

Background competition is represented by the mean of stand basal area per hectare (BA). Its sampling variation is simply the standard error of the mean basal area of the subplots in the stand. The measure of competition for trees within a subplot is the product of basal area per unit area at that particular subplot multiplied by the percentile of the subject tree in the diameter distribution of all trees in the stand. Because this index is analogous to the basal area in larger trees introduced by Wykoff *et al.* (1982) and Wykoff (1990) and used in many increment models, we continue to refer to it as BAL. Because the single plot does not provide a sample-based estimate of its basal-area variance, we derive a first approximation to the sampling error of BAL as a function of the basal area variance in a Poisson (random) field of stem locations, the percentile, and the total stem count in all subplots (Stage and Wykoff 1998).

Comparison to Ordinary Least Squares (OLS) Estimation

Differences between the structural model and an ordinary least squares model of some northern Idaho inventory data are shown in several figures; figure 2 shows remarkable changes in the effect imputed to crown ratio (including the term that depends on dbh). Note the complete reversal of the trend with dbh. Differences in predicted diameter increment are illustrated in figures 3-5 (Wykoff 1997). Both BA and BAL were competition variables for which sampling variances were estimated. Because BAL is computed from basal area at the sample point occupied by the subject tree and BA is a stand average, allowing for their relative sampling variation greatly increases the sensitivity of the model to local competition effect (fig. 3). But differences are not limited to effects of variables measured with sampling error. The effect of dbh also changes markedly (fig. 4). In this, as in many similar models, crown ratio can be the alias for direct effects of competition. Explicitly recognizing the error variance of the competition variables shifts competition effects from the crown ratio term to the competition terms (fig. 5). In analyses of thinning effects, the immediate response will be greater because crown ratio takes some time to regain its natural correlation with stocking.

We compared the effect of two different sampling designs on the relative behavior of the SBP-based model. The "stand" for which the simulations are calculated was generated by the Regeneration submodel of the Inland Empire variant of the Forest Vegetation Simulator (Prognosis). From this stand projection, a "patchy" stand was created having equal area of each of three age classes. Means of 20 simulations of two scenarios—thinned, and

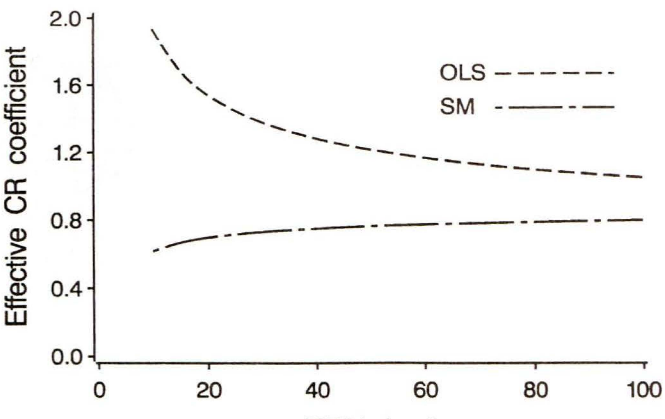


Figure 2.—*Effect of crown ratio on prediction of ln(DDS) in the structural model is very different from its effect in the ordinary least squares model because of correlation with the competition variables.*

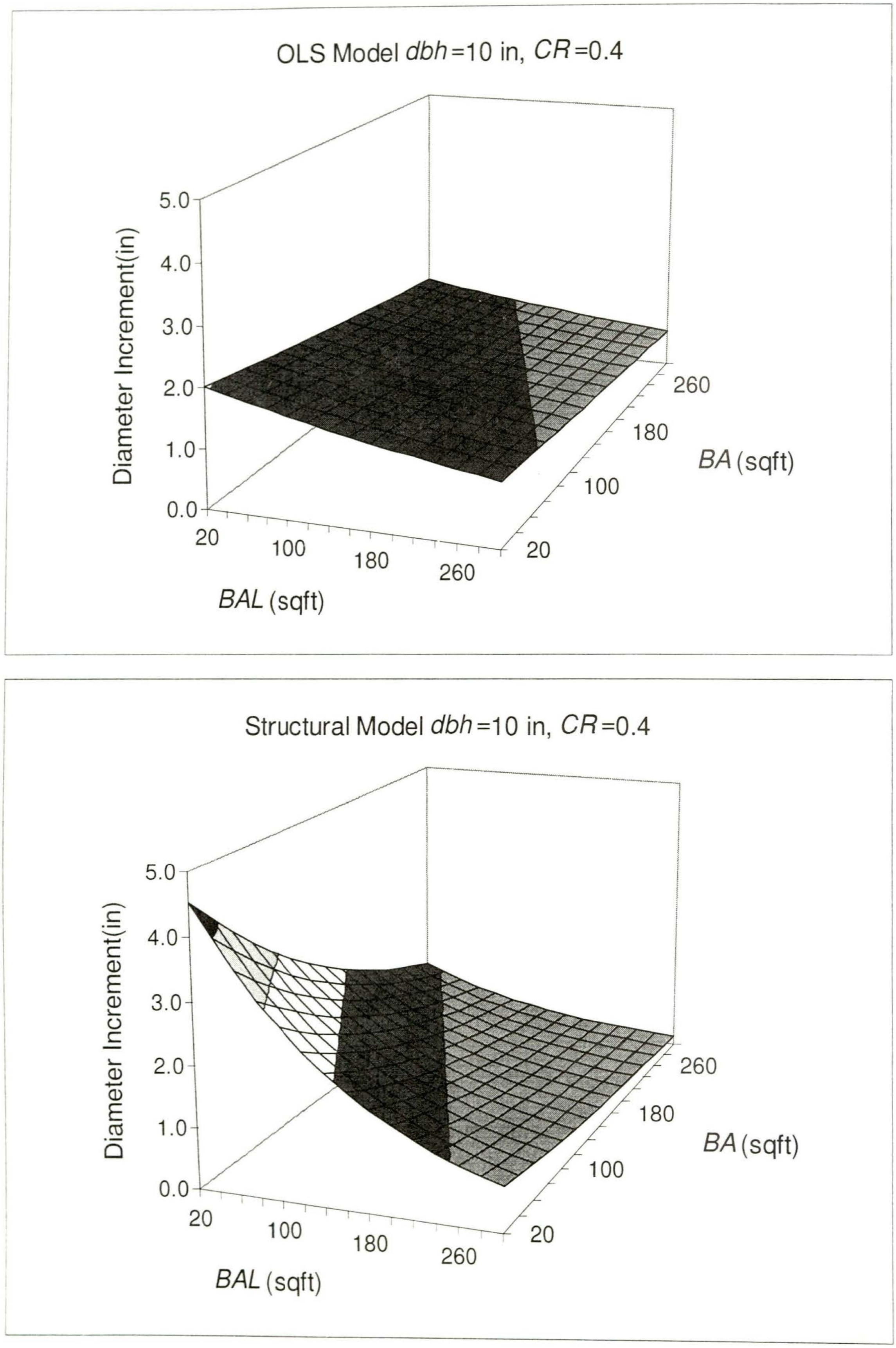
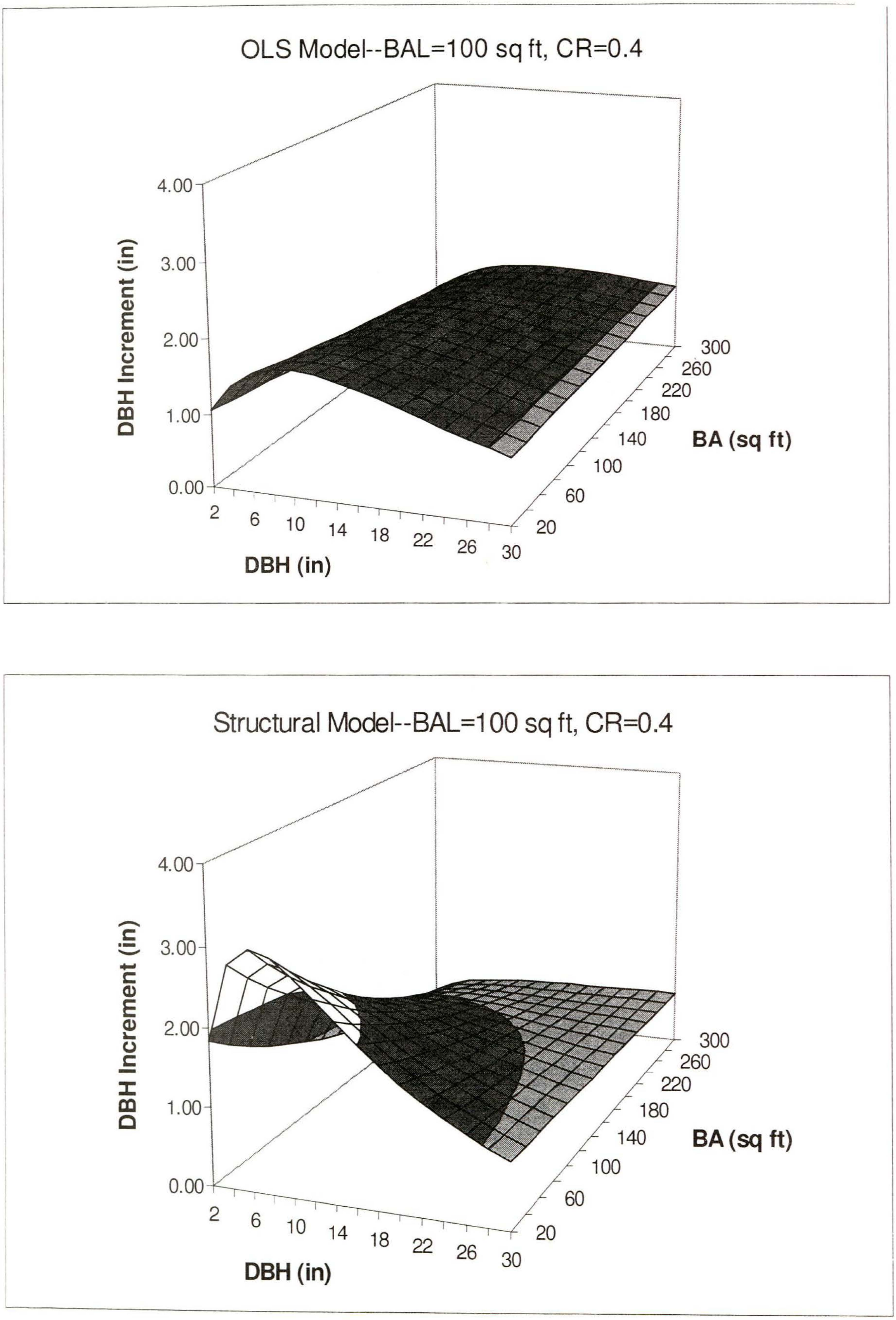


Figure 3.—*Differences in response surface between ordinary least squares model (OLS) and structural model (SM)—varying BAL and BA.*


OLS Model--BAL=100 sq ft, CR=0.4

Structural Model--BAL=100 sq ft, CR=0.4

Figure 4.—*Differences in response surface between ordinary least squares model (OLS) and structural model (SM)—varying DBH and BA.*

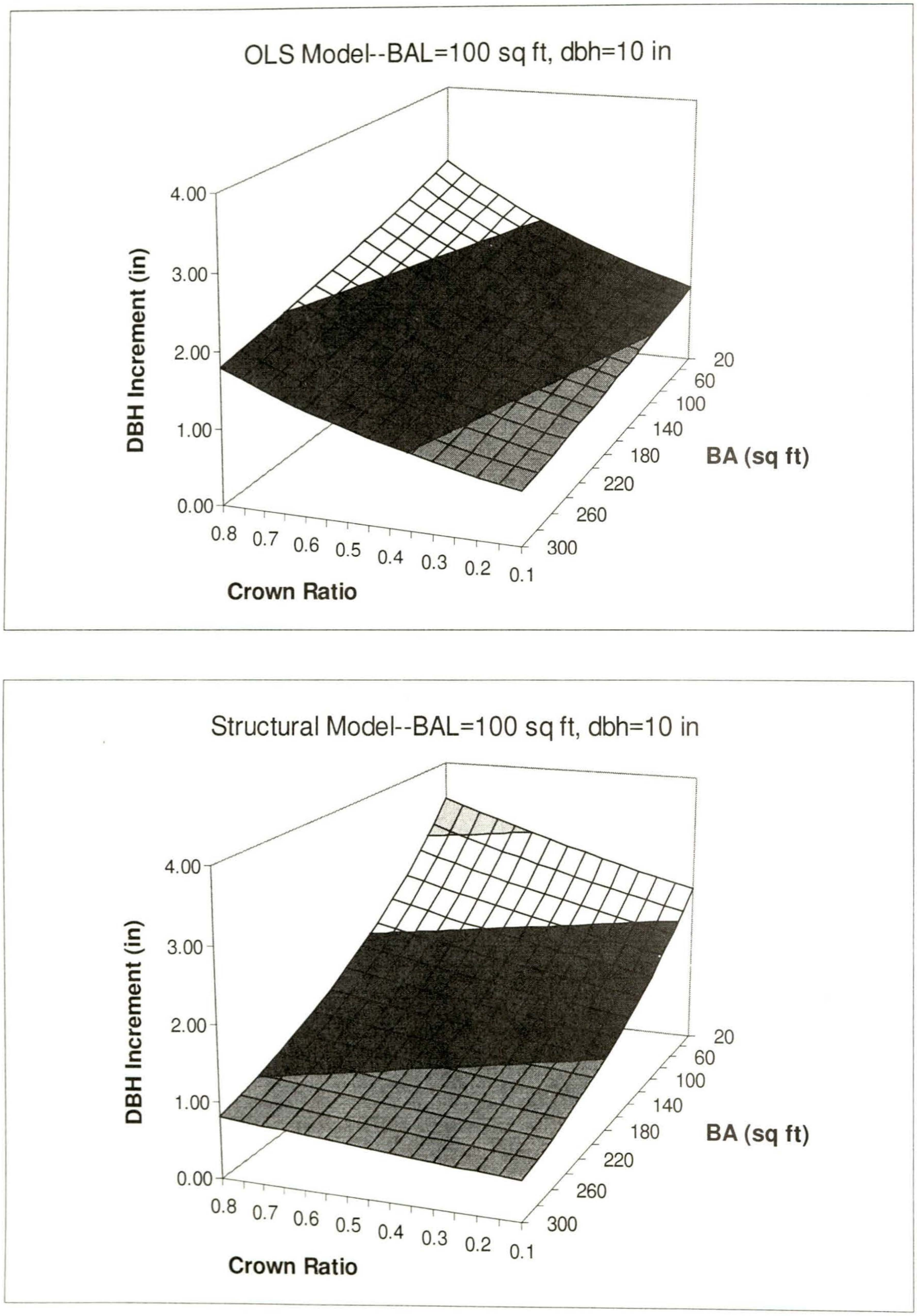


Figure 5.—*Differences in response surface between ordinary least squares model (OLS) and structural model (SM)—varying CR and BA.*

unthinned—are compared. The differences between the two inventory methods are the result of simulating the stand as if initially "inventoried" by 24 plots—each 1/300 acre (0.00135 ha), or as if inventoried by a single plot of 1 acre (2.47 ha.). The model calibration data were actually inventoried by variable-radius plots invariably larger than 1/300 acre (0.00135 ha).

For the more uniform stand left after thinning, projections are nearly coincident (fig. 6). It could be inventoried either way. However, the single-plot projections of the unthinned stand are almost parallel to the thinned projection, indicating little response to thinning. The 24-plot projection of the unthinned stand, by comparison, increases less rapidly, which indicates that there was an immediate response to the thinning.

IMPLICATIONS FOR INVENTORY DESIGN

This development in growth modeling raises new questions about optimal inventory design. Because we make explicit use of statistical effects of varying plot size as part of the increment estimation process, we can evaluate the tradeoff between optimizing the statistical precision and optimizing the resolution with which the biological processes can be represented. Now relations between subplot size and number and the diameters of trees can be varied to capture the biological structure of the stand, thereby sharpening the portrayal of future development. In turn, thinning algorithms used in simulations can base thinning decisions on local conditions in much the same way that a silviculturist would treat different parts of the same stand.

Sampling errors used in SBP for the two competition variables, BA and BAL, depend on size and number of the subplots. Size of plots can be varied, but they should be small enough that all trees in a single plot are close enough to interact through, say, no more than one intermediary. Representation of the biological structure of the stand can be improved by a design using plot sizes that increase with tree diameter—either smoothly as in "prism plots," or in several steps as in nested plots. Circular plots are preferred over rectangular because they have less edge. The BAL variable is favored in two respects by sampling with variable-sized plots. First,

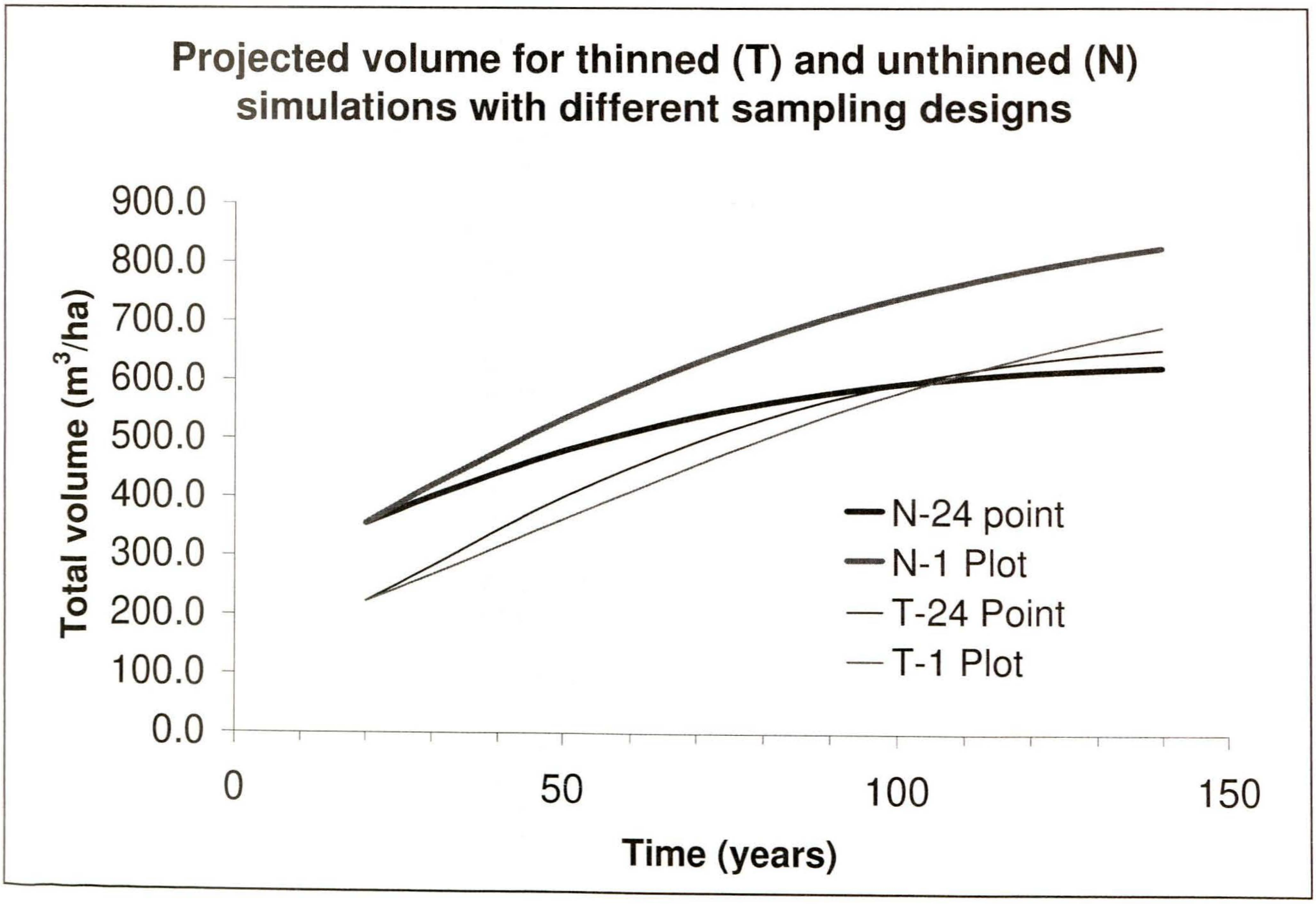


Figure 6.—*Differences in projections of a patchy stand attributable to the sampling design describing the stand to be projected. Two scenarios are compared: thinned vs. unthinned.*

trees larger than the subject tree are sampled on larger plots so that fewer of its competing trees would be "off plot." And second, efficiency with which the basal area component is estimated is increased in comparison to fixed-area plots.

Here to fore, the only use of variance among plots in a cluster or stand has been to optimize estimates of population means or totals. While at least two subplots per location provide an estimate of sampling variance of mean BA, the variance of the variance is high for two to three plots per location. For example, in an infinite population, the variance of the sample estimate of the variance is:

$$V\left(s^2\right)=\frac{2\,\sigma^4}{n-1}\left[1+\frac{n-1}{2n}G_2\right]$$

where G2 is the Fisher measure of kurtosis.
Note, however, that the biases in the predictions with SBP now depend on variances of variances, rather than on just the variance as with OLS.

CONCLUSIONS

In this paper, we addressed the question of how inventory design affects use of inventory data for analyzing alternative management scenarios. The false assumption that competition variables are known without sampling error was shown to have substantial effects on coefficients of models. The procedure we call Structural Based Prediction was demonstrated using a semi-distance-independent growth model as example. Implications of SBP for inventory design were discussed in the context of using inventory data and a growth model to project future stand attributes and to evaluate silvicultural alternatives.

ACKNOWLEDGMENTS

The following people reviewed this paper: Dr. Kelsey Milner, University of Montana, Missoula, MT, USA, and Dean Stuck, Potlatch Corp., Lewiston, ID, USA.

LITERATURE CITED

Elliot, W.J.; Hall, D.E. 1997. Water Erosion Prediction Project (WEPP) forest applications. Gen. Tech. Rep. INT-365. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 11 p.

Fuller, W.A. 1987. Measurement error models. New York, NY: John Wiley and Sons. 440 + xxiii p.

Goelz , J.C.G.; Burk, T.E. 1996. Measurement error causes bias in site index equations. Canadian Journal of Forest Research. 26: 1585-1593.

Jaakkola, S. 1967. On the use of variable size plots for increment research. In: Anonymous, ed. Vol VI, Proceedings XIV International Union of Forestry Research Organizations Congress Sect 25; Munich, Germany: 371-378

Kangas, A.S. 1998. Effect of errors-in-variables on coefficients of a growth model and on prediction of growth. Forest Ecology and Management. 102: 203-212.

Lappi, J. 1991. Estimating the distribution of a variable measured with error: stand densities in a forest inventory. Canadian Journal of Forest Research. 21: 469-473.

Pauley, G.R.; Peek, J.M.; Zager, P. 1993. Predicting white-tailed deer habitat use in northern Idaho. Journal of Wildlife Management. 57: 904-913.

Schreuder, H.T.; Williams, M.S. 1995. Assessing measures of tree competition using fixed-area, variable-radius, and horizontal-line sampling. Canadian Journal of Forest Research. 25: 1578-1582.

Stage, A.R. 1977. Forest inventory data and construction of growth models. In: Schmid-Haas, P., ed. Inventories on successive occasions. Papers presented at the XVIth IUFRO World Congress in Oslo, June 20-July 2, 1976. Berichte Nr. 171, Eidgenössische Anstalt für das forstliche Versuchswesen CH8903 Birmensdorf.

Stage, A.R.; Wykoff, W.R. 1993. Procedure for representing spatial variability within distance-independent stand growth models: an application of measurement error models. In: Burkhart, *et al.*, eds. Modeling stand response to silvicultural practices. Proceedings of the IUFRO S4.01 conference; 1993 September 27-October 1; Blacksburg, VA. Pub. FWS-1-93. Blacksburg, VA: College of Forestry and Wildlife Resources, Virginia Polytechnic Institute and State University: 131-144.

Stage, A.R.; Wykoff, W.R. 1998. Adapting distance-independent forest growth models to represent spatial variability: effects of sampling design on model coefficients. Forest Science. 44(2): 224-238.

Wykoff, W.R.; Crookston, N.L.; Stage, A.R. 1982. User's guide to the stand prognosis model. Gen. Tech. Rep. INT-133. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 112 p.

Wykoff, W.R. 1990. A basal area increment model for individual conifers in the northern Rocky Mountains. Forest Science. 36: 1077-1104.

Wykoff, W.R. 1997. Predicting basal area increment in irregular stands: a progress report. In: Teck, *et al.*, comps. Proceedings Forest vegetation simulator conference; 1997 February 3-7; Fort Collins, CO. Gen. Tech Rep. INT-373. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 199-205.

Evaluating A Model To Predict Timber Harvesting In Austria

Hubert Sterba, Michael Golser, and Klemens Schadauer

Abstract.—Between 1981 and 1985, the Austrian National Forest Inventory (ANF) established a set of 5,500 clusters, each with four permanent plots, covering all Austrian forests. After the first remeasurement between 1986 and 1990, models were developed to predict tree growth, mortality, and the behavior of forest owners in harvesting timber. A set of logistic equations describes the probability of a given stand exhibiting intermediate harvesting, single-tree selection, or final clearcutting. The independent variables were partly continuous and partly categorial, describing (1) regional units such as provinces, (2) types of ownership (groups of ownership sizes), (3) site factors (elevation and slope), and (4) stand characteristics (species mixture, density, mean diameter). The removal in the plots is given by five relative dbh classes. These removal percentages differ by elevation, harvesting categories, and tree species groups. A forecast of timber harvests in their spatial arrangement over Austria in the following four 5-year periods was made available to the public on a compact disk. In 1997, data from the second inventory remeasurements were available, and thus the forecasts for this period could be evaluated. Provided the units for which the forecasts were done are large enough, the results indicate that the deviations from the model are either small or can be explained by a then different timber market scenario and/or general socioeconomical scenario.

Austrian forests cover about 3.9 million ha or 47 percent of the country's total area, and 85 percent of these forests are exploitable. The forest owners are typically nonindustrial owners, who sell their timber to the forest industry. The ownerships are usually small (15 ha average), and only 20 percent of the forest area is public forest. Two-thirds of the owners own fewer than 2 ha, and approximately 50 percent of the forest area belongs to owners with fewer than 200 ha (Bundesministerium für Land- und Forstwirtschaft 1995; fig. 1). Forest industries, especially the sawmills, typically (with some exceptions) do not possess their own forests. As with forest owners, the small sawmills outnumber the big ones. Fifty percent of the yearly roundwood is processed by sawmills that process less than 100,000 m³ per year (fig. 2). In 1996, therefore, the Association of the Austrian Sawmilling Industries ordered the development of software that would enable a single sawmill or any other user to get forecasts of timber harvests for an interactively definable region within Austria by tree species and a number of other categories for four 5-year periods (fig. 3).

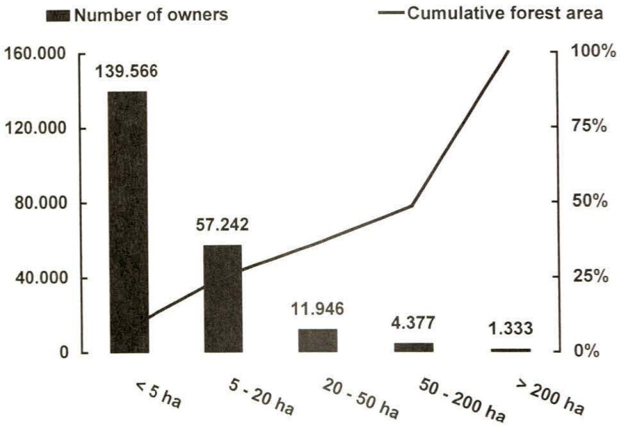


Figure 1.—*Forest ownership structure in Austria (source: Bundesministerium für Land- und Forstwirtschaft 1995).*

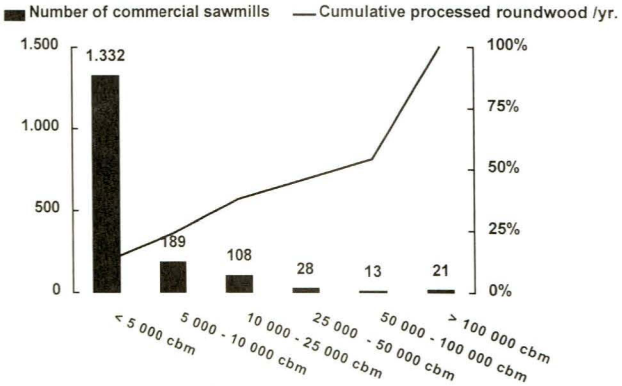


Figure 2.—*Sawmill structure in Austria (source: Fachverband der Sägeindustrie Österreichs 1997).*

Professor and Research Assistant, Institute for Forest Growth and Yield, Universität für Bodenkultur Wien, Peter Jordanstraße 82, A-1190 Vienna, Austria; and Federal Forest Research Center, Seckendorff-Gudent-Weg 8, A-1131 Vienna, Austria, respectively.

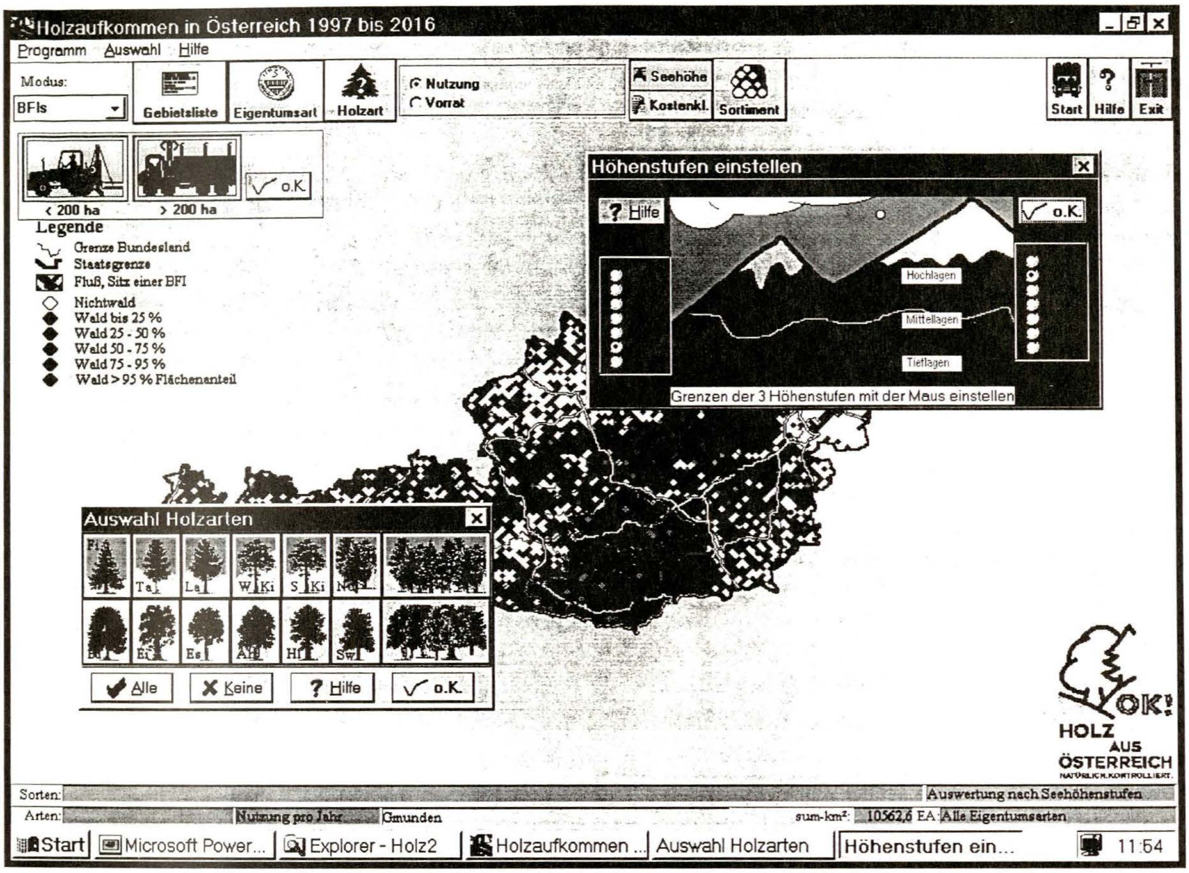

Holzaufkommen in Österreich 1997 bis 2016
Programm
Auswahl
Hilfe
Modus:
BFIs
Gebietsliste
Eigentumsart
Holzart
Nutzung
Vorrat
Seehöhe
Kostenkl.
Sortiment
Start
Hilfe
Exit
< 200 ha
> 200 ha
o.K.
Legende
Grenze Bundesland
Staatsgrenze
Fluß, Sitz einer BFI
Nichtwald
Wald bis 25 %
Wald 25 - 50 %
Wald 50 - 75 %
Wald 75 - 95 %
Wald > 95 % Flächenanteil
Höhenstufen einstellen
Hilfe
o.K.
Hochlagen
Mittellagen
Tieflagen
Grenzen der 3 Höhenstufen mit der Maus einstellen
Auswahl Holzarten
Fi
Ta
La
WKi
SKi
Nd
Bu
Ei
Es
AH
Hl
Sw
Alle
Keine
Hilfe
o.K.
OK!
HOLZ
AUS
ÖSTERREICH
NATÜRLICH KONTROLLIERT.
Sorten:
Auswertung nach Seehöhenstufen
Arten:
Nutzung pro Jahr
Gmunden
sum-km²:
10562,6
EA:
Alle Eigentumsarten
Start
Microsoft Power...
Explorer - Holz2
Holzaufkommen ...
Auswahl Holzarten
Höhenstufen ein...
11:54

Figure 3.—*Interactive selection of regions, tree species, ownership classes, and other categories for timber harvest forecasts with PROGNAUS.*

DATA

To mimic the behavior of Austrian forest owners, a harvesting model was built, based on the data of the Austrian National Forest Inventory (ANF) from two observation periods, 1981-1985 and 1986-1990. This inventory is a permanent sample over the whole of Austria. The sample plots are clustered at the four corners of a 200- × 200-m square. The clusters themselves are systematically distributed over Austria at a distance of 3.89 km apart. In any given year, every fifth cluster is measured, ensuring a representative sample of all Austrian forests each year. The total inventory comprises 5,500 clusters, consisting of 22,000 sample plots. The center of each plot was marked by a hidden iron stake buried underground. Trees with a diameter at breast height (dbh) larger than 10.4 cm were selected by angle count sampling (Bitterlich 1948) with a basal area factor of 4 m^2 ha^{-1}. Trees with dbh between 5 cm and 10.4 cm were measured only within a circle of 2.6 m radius. Each sample tree was recorded by its polar coordinates and marked by a nail at the base of the tree. These plots were remeasured in five overlapping 5-year intervals, thus covering the period from 1981 to 1990. For the objective of this paper, i.e., the evaluation of the harvest model, data from the second remeasurement of the plots in 1992 to 1996 were used.

THE MODELS

From the first remeasurement of the forest inventory, an individual tree growth simulator of the FVS type, PROGNAUS, (Monserud *et al.* 1997) was built, consisting of a basal area growth model (Monserud and Sterba 1996), a height growth model (Knieling 1994), a crown ratio model (Hasenauer and Monserud 1996) and a mortality model (Monserud and Sterba 1999). To develop software to forecast timber harvests, Moser (1996) added a harvest model, simulating the behavior of forest owners in harvesting trees in their forests. Since all the above-mentioned models were developed for a 5-year period (according to the database) and the forecasts had to be made for 20 years, some additional models, such as to establish ingrowth and to describe the change of the forest development type (youth, thicket, pole stage, mature, uneven-aged), were built to update the data after each 5-year forecast.

For the harvest model at the plot level, a stochastic approach was used, distinguishing between four kinds of harvests:

1. regular final harvests,
    1.1 clearcuts (defined by the ANF as removing all trees on an area larger than 500 m^2)
    1.2 single-tree harvests
2. regular intermediate thinnings, and
3. salvage cuts, i.e., harvests needed because of damage from snow, windthrows, insects, or fungi.

The probability of any of the above harvests taking place on a given inventory plot was depicted by a LOGIT-function of the general form

$$P(harvest) = LOGIT(X) = \frac{1}{1+e^{b^T X}}$$

with X the vector of independent variables and b the associated coefficients. The CATMOD-procedure (SAS Institute 1987) was used to estimate the parameters of the logistic equation using maximum likelihood methods. In detail, there were four such equations, building a system in which only the underlined (fig. 4) probabilities (regular harvest, final harvest, salvage cut, and clear cut) need to be distinguished:

(1) Equation to determine the probability for any regular harvest on a plot,

$$P(\text{regular harvest}) = LOGIT(dg, h_L, BA, CV, ELEV, PF, HC1, HC2, DIST, PROV1, CON, MIX)$$

with dg, the dbh of the mean basal area stem, h_L, Lorey's mean height, BA, basal area per hectare, CV, the coefficient of variation of the dbh distribution, and $ELEV$, the elevation. All the other parameters are dummy variables (Draper and Smith 1981): PF equals 1, if the plot is situated in a protection forest, $HC1$ is equal to 1 if the slope is less than 30 percent, $HC2$ is 1 if the surface at the plot was classified as difficult for harvesting operations (through soil groups), $DIST$ is 1 if the distance to the next rack or forest road is less than 100 m, $PROV1$ is 1 in the province of Tyrol, CON is 1 if the proportion of conifers (by basal area) is larger than 25 percent, and MIX is 1 if the proportion of conifers is between 25 and 75 percent, all otherwise 0.

(2) Equation for salvage cuts, conditioned on no regular harvest

$$P(\text{salvage} \mid \neg\text{regular harvest}) = LOGIT(dg, h_L, BA, CV, OW, HC1, PROV1, PROV2, CON)$$

where OW is 1 if the plot is situated in a forest ownership of less than 200 ha, $PROV2$ is 1 in the province of Salzburg, and the other variables are as given above.

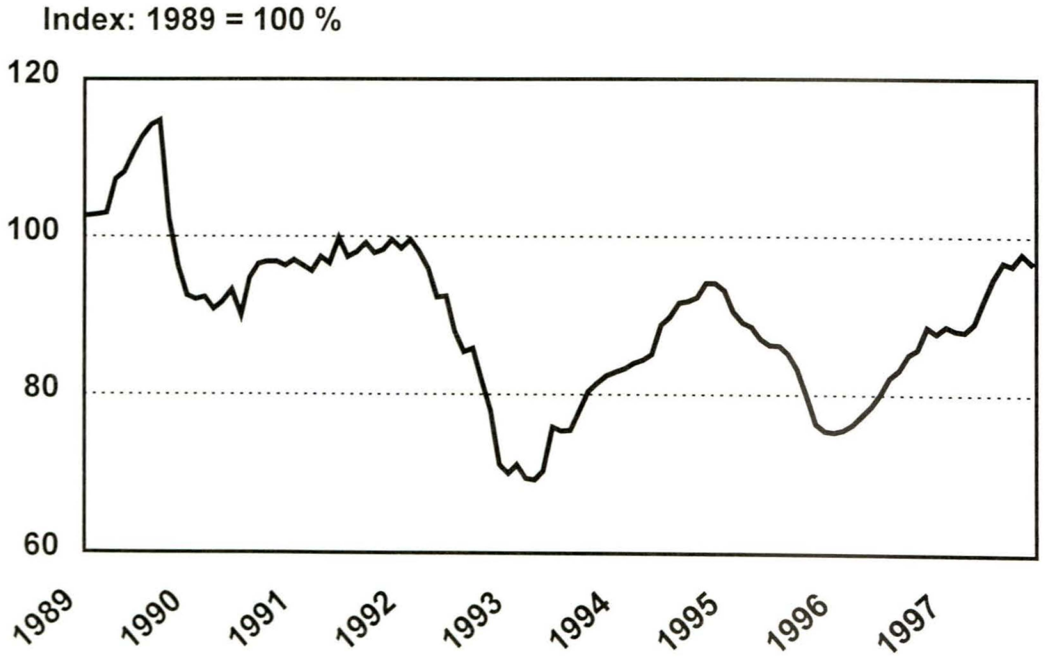


Figure 4.—*Decision tree for simulating harvest at the plot level.*

(3) Equation for final harvest, conditioned on regular harvest

$$P(final \mid regular) = LOGIT(dg,\ h_L,\ BA,\ CV,\ OW,\ PF,\ CON)$$

(4) Equation for clearcuts, conditioned on final harvest

$$P(clear\_cut \mid final) = LOGIT(dg,\ BA,\ ELEV,\ PF)$$

The forecasts, finally made available on a CD, were the results of 500 runs for each period; by random numbers in comparison with the calculated appropriate probability, it was decided which, if any, category of harvest was to take place at the plot level.

After this, harvest at the tree level was simulated by the following procedure. Each sample tree on the plot was related to one of five dbh classes, each comprising about the same number of trees per hectare. Thus, for each tree, the relative dbh was defined as

$$d_{rel} = \frac{dbh - dg}{s_{dbh}}$$

with s_{dbh} the standard deviation of the dbh on a plot.

The allocation of a sample tree into one of the five dbh classes followed the assumption of normal distribution of basal area over dbh; thus, the 20th, 40th, 60th, and 80th percentiles of the normal distribution were the breakpoints for the five dbh classes.

Tables for average basal area removal percentage in these dbh classes were calculated for a total of 60 strata, built according to species groups, elevation classes, groups of provinces, and harvesting categories. The examples (table 1) demonstrate how the removals differed between harvest categories and species. In the clearcuts, nearly all trees in all dbh classes were removed; some shelterwood trees were left, but not concentrated in a certain dbh class. To also retain seed trees of beech (*Fagus silvatica, L.*), the removals of beech on clearcuts were somewhat less than those of Norway spruce (*Picea abies L.* Karst.), except in the smallest dbh class. In the intermediate thinning, the removals clearly decreased with increasing dbh and again were less intensive in beech compared with spruce. In spruce, final single-tree harvests seemed to increase with increasing dbh (target diameter harvest according to Reininger 1989), while in beech, single-tree harvests as well as salvage cuts were about uniformly distributed over the dbh classes. Salvage cuts in spruce were concentrated around the average dbh.

In the final tree-harvest model, the basal area, represented by every tree in the plot, was reduced by the percentages given in the appropriate table.

EVALUATION OF THE HARVEST MODEL

The actual harvest was calculated from the repeated forest inventory of 1992-1996, so the plots last measured in 1986 were measured again in 1992, those measured in 1987 in 1993, and so on. Because this inventory period covered 6 years, while the simulator PROGNAUS was built for 5-year periods, the harvests reported by the inventory had to be multiplied by 5/6 to compare with the forecasts of PROGNAUS.

The various comparisons were made twice, first for the whole of Austria, and second—as the example chosen—for a region that could have been selected by a sawmill situated in eastern Carinthia and wanting to know the

Table 1.—*Example for the harvesting model at the tree level. Norway spruce and common beech in one of the 60 site strata. Percent basal area removal in five relative dbh classes with approximately equal initial tree numbers is given by harvesting categories.*

		Relative dbh-class				
Species	**Harvest category**	**1**	**2**	**3**	**4**	**5**
Norway spruce	Clearcut	72.4	100.0	72.6	86.3	77.6
	Single tree selection	22.4	23.9	18.7	32.5	33.0
	Intermediate thinning	60.2	40.1	27.8	18.0	7.9
	Salvage cut	20.2	30.1	38.8	12.7	9.8
Common beech	Clearcut	92.5	62.2	60.2	77.5	75.2
	Single tree selection	32.4	23.0	22.1	18.5	20.2
	Intermediate thinning	39.9	33.0	19.7	9.4	10.0
	Salvage cut	28.0	20.0	28.1	19.2	30.0

probable timber yield within a circle of approximately 60 km around the sawmill. Compared with the Austrian average, the average elevation of this region is somewhat higher, there are more spruce and fewer broadleaves, protection forests are less, and small forest ownerships are even more frequent in this region (table 2).

Table 2.—*Characteristics of the selected region in comparison with the average of Austria*

	Austria	Selected region
Elevation [m]	905	1,062
Protection forest area [%]	7.4	5.1
Small forest ownership area [%]	53	70
Norway spruce volume [%]	61	72
Broadleaf tree volume [%]	16	9

For both areas, Austria and the selected region, harvests will be compared in terms of fellings in m³. In the future, the proportions of total harvested volume with respect to management types (protection forest, commercial forests), elevation, harvest categories (intermediate thinning, single-tree selection, final clearcuts), dbh classes, and tree species will be compared. Because of the large number of plots and sample trees, practically any deviation from the forecasts is expected to be significant. Of interest is not the statistical significance, but rather the magnitude of the deviations of predicted volume proportions by categories. Therefore, a simple distance measure (Dirk 1995) for this deviation was defined as

$$\text{Distance [\%]} = \sum_{Categories} \left| f\%_{observed} - f\%_{PROGNAUS} \right|$$

with *f%* the observed and predicted proportion of harvested volume in the given category, and Distance% covering a range between 0 (no deviation, full fit) and 200 percent (maximum deviation).

RESULTS

For the whole of Austria, the total actual timber harvest was about 10 percent smaller than predicted, while for the selected region, the difference was not so large. Nevertheless, in both reference areas, harvests in the small ownerships were distinctly overestimated (table 3). This overestimation is one more reason to later compare relative volume proportions by categories rather than absolute volume in m³. The distances between the distribution of volume to categories are given in table 4.

Table 3.—*Fellings by ownerships and harvest categories as observed by the Austrian Forest Inventory (ANF92/96) and predicted by PROGNAUS in 1,000 m³ o.b. Δ% is the overestimation or underestimation of the actual harvests by the model (in percent).*

Harvest category	Size of ownership	Austria			Selected region		
		ANF 92/96	PROGNAUS	Δ%	ANF 92/96	PROGNAUS	Δ%
Regular harvest	< 200 ha	8,425	10,031	+19	2,105	2,215	+5
	> 200 ha	7,559	7,559	+4	910	860	-6
	Σ	15,984	17,871	+12	3,015	3,075	+2
Salvage cuts	< 200 ha	935	687	-26	191	149	-22
	> 200 ha	1,007	1,362	+35	105	124	+18
	Σ	1,941	2,050	+6	296	273	-8
Σ	< 200 ha	9,360	10,718	+14	2,296	2,364	+3
	> 200 ha	8,566	9,202	+7	1,015	984	-3
	Σ	17,926	19,920	+11	3,311	3,348	+1

Table 4.—*Distance (%) between harvest volume distributions*

Grouping		**Austria**		**Selected region**	
		Regular harvest	**Salvage cut**	**Regular harvest**	**Salvage cut**
Elevation		7.28	41.17	9.47	39.94
Management type		0.90	3.40	0.98	2.52
Harvest category		10.71	-	11.56	-
Dbh-class		7.26	13.33	8.75	25.98
Tree species within	intermediate thinning	10.88	-	8.19	-
	single tree selection	12.88	-	21.45	-
	clearcut	9.60	-	5.18	-
	total	6.40	10.89	8.77	7.65

Obviously, and not unexpectedly, the predictions were somewhat worse for the salvage cuts and in the selected, and thus smaller, region. To illustrate the magnitude of the deviations between predicted and observed volume distributions, table 5 depicts the respective dbh distribution. For the whole of Austria as well as for the selected region, the regular harvest—dbh distribution was quite well predicted by PROGNAUS, whereas for salvage cuts, the harvests in smaller dbh classes seem to have been underestimated. This shift to smaller dbh classes was even stronger for the selected region than for all over Austria.

Given that distances above 10 indicate some important deviations from the predicted distribution, the distribution of salvage cuts to elevation classes (table 6), the distribution of regular harvests to harvest categories (intermediate thinning, final single-tree selection and clearcuts, table 7), and species distribution, especially in single-tree selections (table 8), exhibited interesting deviations from the model.

DISCUSSION

Total Harvest

The first and most important result to discuss is the overestimation of the total harvests. Nearly all of these 2 million m^3 overestimates are located in regular harvests of small forest ownerships (table 3). Severe storm damages in forests, only partly in Austria but mainly in the neighboring German (Bavarian) forests in 1990, were followed

Table 5.—*Harvested volume distribution by dbh classes (percent of volume) as observed (ANF 92/96) and predicted (PROGNAUS)*

			Dbh [cm]							
			< 10	**15**	**25**	**35**	**45**	**55**	**65**	**>70**
Austria	Regular harvest	ANF 92/96	4.1	14.6	21.2	24.7	18.9	11.0	3.6	2.0
		PROGNAUS	3.1	13.4	23.2	25.9	18.6	10.0	3.6	2.3
	Salvage cuts	ANF 92/96	2.3	12.7	23.1	26.1	19.6	9.3	4.1	2.9
		PROGNAUS	1.7	9.4	20.6	27.8	21.2	11.9	4.5	3.0
Selected region	Regular harvest	ANF 92/96	3.9	14.3	22.8	24.3	18.4	11.5	3.1	1.9
		PROGNAUS	3.0	13.6	24.1	27.3	17.7	9.7	2.9	1.8
	Salvage cuts	ANF 92/96	4.3	18.1	25.5	23.9	10.4	11.9	3.1	2.9
		PROGNAUS	2.1	12.0	23.5	27.8	18.5	10.2	3.5	2.3

Table 6.—*Harvested volume distribution by elevation classes (percent of volume) as observed (ANF 92/96) and predicted (PROGNAUS)*

			Elevation [m]						
			< 500	600	800	1,000	1,200	1,400	>1,500
Austria	Regular harvest	ANF 92/96	23.8	17.6	17.7	13.4	12.5	9.3	5.8
		PROGNAUS	22.2	18.2	16.6	14.0	14.2	9.0	5.9
	Salvage cuts	ANF 92/96	22.2	15.9	22.6	10.5	13.5	11.2	4.3
		PROGNAUS	10.2	13.3	16.6	17.5	17.7	11.6	13.1
Selected region	Regular harvest	ANF 92/96	5.9	15.3	15.7	18.3	19.0	16.0	9.8
		PROGNAUS	7.2	16.6	15.1	19.0	20.0	16.1	6.0
	Salvage cuts	ANF 92/96	12.8	4.7	18.8	24.4	15.6	21.6	2.1
		PROGNAUS	5.1	12.7	14.6	19.2	20.9	18.8	8.8

Table 7.—*Distribution of observed (ANF 92/96) and predicted (PROGNAUS) harvested volume by harvesting categories. Values given are percent of harvested volume. Intermediate thinning, single-tree selection and clearcuts are related to regular harvests, while salvage cuts are related to total harvests.*

	Austria		Selected region	
Harvesting category	ANF 92/96	PROGNAUS	ANF 92/96	PROGNAUS
Intermediate thinning	16.9	12.3	17.3	13.6
Single-tree selection	35.5	35.6	31.6	37.2
Clearcut	36.8	41.8	42.1	41.1
Salvage cuts	10.8	10.3	8.9	8.2

Table 8.—*Distribution of observed (ANF 92/96) and predicted (PROGNAUS) harvested volume by species in percent of final single-tree selections*

	Austria		Selected region	
Species	ANF 92/96	PROGNAUS	ANF 92/96	PROGNAUS
Norway spruce (*Picea abies* L.)	58.2	59.8	64.8	72.1
White fir (*Abies alba* L.)	6.7	5.4	2.4	2.3
European larch (*Larix europaea* L.)	4.8	4.4	9.9	7.5
Scots pine (*Pinus silvestris* L.)	12.1	8.3	12.5	7.2
Common beech (*Fagus silvatica* L.)	6.9	8.8	1.1	4.3
Oak (*Quercus* sp.)	3.7	2.8	1.4	0.6
Other deciduous	7.1	9.8	7.9	5.8

by a bark beetle outbreak that lasted until about 1996 (Forstliche Bundesversuchsanstalt 1996). Partly for this reason and partly because of low world market sawnwood prices, the timber prices decreased seriously and have not yet fully recovered (fig. 5). Among the forest owners, only those with small land holdings, who do not really depend on the income from forestry, are able to react to such fluctuations of timber market prices (Schwarzbauer 1997). So, the storm damages of 1990, together with the following timber market situation, seem to have led small forest owners to decrease their harvests.

Distribution by Different Categories

As indicated by the average distances (table 4), the relative distribution of harvested volume to most of the different categories was predicted quite well by PROGNAUS. Those less well predicted are discussed in the following sections.

Salvage Cuts by Elevation and Dbh Classes

The bark beetle outbreak may again be the reason why salvage cuts shifted to lower elevations (table 6) to smaller dbh classes than expected from the inventory period 1981-1990 and thus the model. Due to the biology of *Ips typographus* and *Ips chalcographus*, forests in lower elevations and smaller trees there are more susceptible to bark beetle attacks. Since by Austrian law, dead trees have to be removed from the forest, the concentration of salvage cuts in these strata after 1990 may be explained by this effect.

Harvesting Categories

Although the proportion of salvage cuts was predicted quite well (table 7), the observed distribution between intermediate thinning, final single-tree selection, and clearcuts within the regular harvests deviated markedly from the PROGNAUS predictions. In the whole of Austria as well as in the selected region, a shift from final harvesting to thinnings seems evident. This means that the decrease in total harvests, compared with PROGNAUS (table 3) and probably caused by decreasing timber prices, concerns final harvests more than thinnings, which are seen more under the aspect of tending and investment in future stand quality. Final single-tree selection is the preferred harvesting method in smaller forest ownerships. That's why in the region with the higher proportion of small ownerships, the decrease in final harvests is charged to single-tree selection, while in Austria, on average, there are fewer clearcuts—both in favor of intermediate thinnings.

Tree Species in Final Single-Tree Selection

One reason for harvesting single trees in old stands is the fact that due to the central European debate on forest

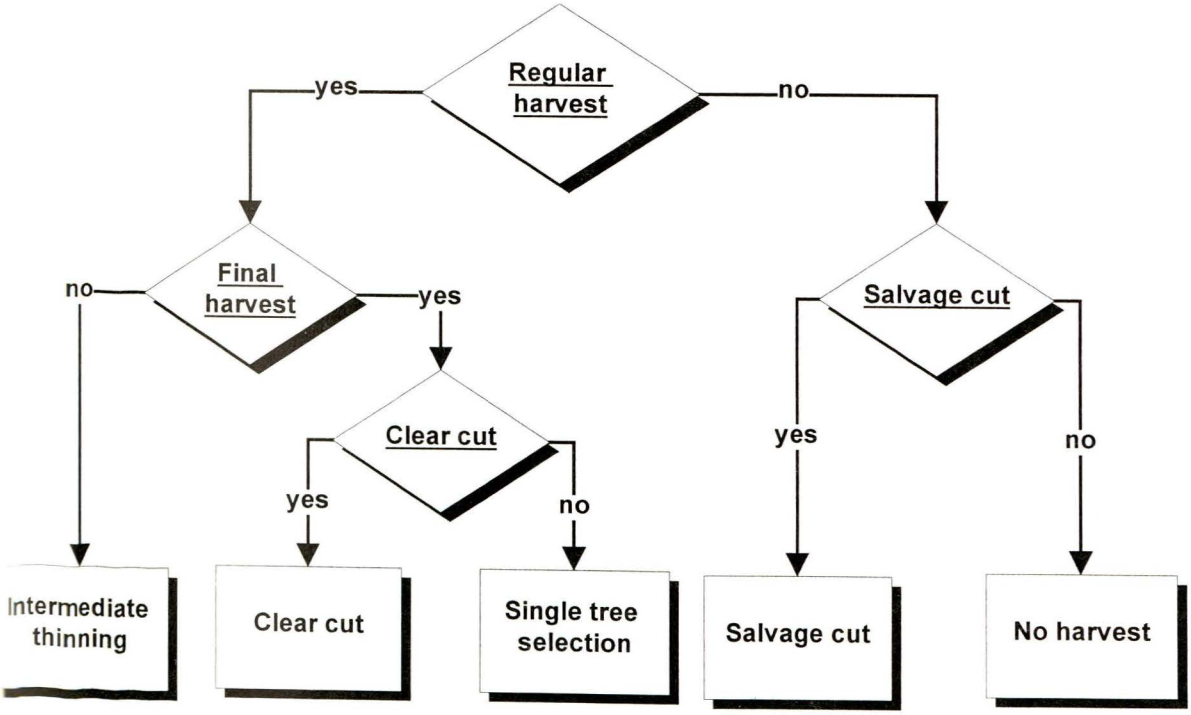


Figure 5.—*Conifer roundwood price development (1988=100%) from Fachverband der Sägeindustrie Österreichs (1997).*

dieback, single trees that by their crown condition seem to indicate poor vigor and probably approaching death are harvested as long as they still live, in the course of "regular" harvesting. If they had already died, they would have been counted as "salvage cuts" in the forest inventory. From the monitoring of crown conditions in Austria, we know that white fir, Scots pine, and oaks are the species with the worst crown conditions over the years (Kristöfel and Neumann 1997). Although the vigor of white fir has improved significantly since 1990, average needle losses of Scots pine and oak have varied strongly, with peaks in 1992 and 1994 (Kristöfel and Neumann 1997). Therefore these species might have been removed more frequently during these periods than predicted by PROGNAUS.

CONCLUSIONS

In general, we conclude that our harvesting model worked quite well. Nevertheless, larger catastrophic events (e.g., windthrows, bark beetle outbreaks, serious changes in crown conditions as a measure of tree vigor) and economic developments cannot be foreseen by PROGNAUS. Including market figures such as roundwood prices in the model, as well as individual tree crown condition, will not be able to improve predictions as long as they themselves cannot be predicted. However, they would enable the model to be used for projections under different scenarios of timber market and "forest dieback" and thus help answer "what-if" questions.

ACKNOWLEDGMENT

The authors want to thank the Association of the Austrian Sawmilling Industries for promoting and sponsoring this work; the Austrian Ministry of Agriculture and Forestry and the Federal Forest Research Center in Vienna, for making the data of the ANF available; and last, but not least, Karl Schieler, head of the ANF, and Peter Schwarzbauer, Professor for Forest Products Market Research at the Universität für Bodenkultur Wien, for valuable review comments.

LITERATURE CITED

Bitterlich, W. 1948. Die Winkelzählprobe. Allg. Forst- u. Holzwirtsch. Zeitung Wien. 59: 4-5.

Bundesministerium für Land- und Forstwirtschaft 1995. Österreichischer Waldbericht 1994. Bundesministerium für Land- und Forstwirtschaft Wien. 266 p.

Dirk W. 1995. Funktionalanalysis. Berlin: Springer Verlag. 446 p.

Draper, N.R.; Smith, H. 1981. Applied regression analysis. 2d ed. New York: John Wiley and Sons. 709 p.

Fachverband der Sägeindustrie Österreichs 1997. Jahresbericht 1997. Informationen des Fachverbandes der Sägeindustrie. (5): 6.

Forstliche Bundesversuchsanstalt 1996. Borkenkäferschäden in Österreich. Forstschutz Aktuell. 17/18: 3-4.

Hasenauer, H.; Monserud, R.A. 1996. A crown ratio model for Austrian forests. Forest Ecology and Management. 84: 49-60.

Knieling, A. 1994. Methodische Beiträge zur Auswertung der Österreichischen Forstinventur nach 1980. Wien: Universität für Bodenkultur. 129 p. Ph.D. thesis.

Kristöfel, F.; Neumann, M. 1997. Ergebnisse der Kronenzustandserhebungen 1996. Österr. Forstzeitung. 107(3): 39-40.

Monserud, R.A.; Sterba, H.; Hasenauer, H. 1997. PROGNAUS. In: Teck, R.; Moer, M.; Adams, J. Proceedings: Forest vegetation simulator conference; 1997 February 3-7; Fort Collins, CO. Gen. Tech. Rep. INT-373. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 50-56.

Monserud, R.A.; Sterba, H. 1996. A basal area increment model for even- and uneven-aged forest stands in Austria. Forest Ecology and Management. 80: 57-80.

Monserud, R.A.; Sterba, H. 1999. Modeling individual tree mortality for Austrian forest species. Forest Ecology and Management. 113(2-3): 109-123.

Moser, M. 1996. PROGNAUS – Simulation des Holzaufkommens für Österreich. Unpublished program description.

Reininger H. 1989. Zielstärken-Nutzung. 3d ed. Wien: Österr. Agrarverlag. 163 p.

SAS Institute. 1987. SAS/STAT Guide for personal computers, Version 6 Edition. Cary, NC. 1028 p.

Schwarzbauer, P. 1997. Demand and supply analysis of roundwood and forest products markets in Europe. EFI Proceedings 17: 7-44.

Remote Sensing Applications in Natural Resource Inventories

A New Sampling Scheme for Tropical Forest Monitoring Using Satellite Imagry

Frédéric Achard, Tim Richards, and Javier Gallego

Abstract.—At the global level, a sampling scheme for tropical forest change assessment, using high resolution satellite images, has been defined using sampling units independent of any particular satellite sensor. For this purpose, a sampling frame has been chosen a hexagonal tessellation of 3,600 km^2.

The stratification has been performed to reduce the variance of the estimated variable. Areas of current (1992-1997) deforestation in the moist zone of the tropical belt have been identified by international consultation. The resulting "hot spot" maps and a forest map derived from NOAA AVHRR 1-km resolution data are used to stratify the sampling population and to determine sampling rates.

Appropriate tropical forest policies must be supported by better informed perspectives on the role those resources play in the global environment. Of major concern is the issue of forest distribution and its rate of change. New information technologies make possible the development of more advanced systems of data gathering and analysis, which can accurately inform us of ongoing changes in the forests of the tropics.

The first phase of the TREES Project was dedicated to the development of global forest cover assessment techniques at the level of the tropical belt. This baseline inventory of tropical forests concerns in order of priority the rain forest biome and adjacent seasonal formations (Malingreau *et al.* 1995).

The concept of TREES was to make wall-to-wall coverage using highly repetitive observations at low resolution. A multi-annual set of AVHRR data was acquired over the whole tropical belt during the period 1991-1994. These data were analyzed to derive a first global tropical forest base map at 1-km resolution. Other investigators have already chosen to map tropical forest area mainly from coarse spatial resolution AVHRR data, most often by using some finer resolution satellite data as a reference data source (e.g., Stone *et al.* 1994). The main advantages of the TREES approach are the daily availability of data (near daily coverage) and the spatial resolution (1.1 km in the case of AVHRR) that is more commensurate to the geographical scale of the monitoring exercise.

However, coarsening the spatial resolution leads to a loss of spatial detail at a rate that depends on the spatial structure of the landscape (Woodcock and Strahler 1987). Consequently the use of coarse spatial resolution maps will effect specific methods, such as the estimation of cover type areas, the validation of results, and the assessment of the product accuracy.

The TREES global assessment has been calibrated using high resolution image maps at selected sites (Mayaux and Lambin 1995). The calibration method developed during the first phase of the project called for the use of Landsat TM data and the design of a specific statistical technique for the production of forest cover figures (Mayaux *et al.* 1998). Ecologically important parameters such as forest cover percentage and fragmentation index have been used as the main variables for the stratification and correction (regression) steps.

OBJECTIVES FOR THE DEVELOPMENT OF A MONITORING SYSTEM

The activities of the first phase were conducted with a view to developing a "prototype" of an operational tropical forest monitoring system: TREES II phase. The operational tropical forest monitoring system should on a regular basis :

- produce relevant and accurate information on the state of the tropical forest resources,
- analyze such information in terms of deforestation trends and possible impacts.

Multi-scale Strategy: Low Resolution Monitoring and High Resolution Sampling

The TREES methodology starts with the identification of "hot spot" areas (Myers 1993) where deforestation is most active, using the combination of individuals' expertise and

---

Achard and Richards, Global Vegetation Monitoring Unit, Gallego, Agriculture and Regional Information Systems Unit, Space Application Institute of the Joint Research Centre of the European Commission, 21020 Ispra, Italy.

a range of remote sensing and ground reference data. Potential indicators such as spatial fragmentation (Jeanjean and Achard 1997) or population increase (Lambin and Ehrlich 1997) are currently being tested to develop a more automatic (i.e., not based on subjective knowledge) detection procedure of the rapid change areas.

Because of the perceived difficulty in deriving accurate measurements for forest change assessment from low resolution data alone (D'Souza and Malingreau 1994, Eva *et al.* 1995), it was decided to estimate the area percentage and the forest change from interpretations of high resolution imagery. A new sampling scheme was deemed indispensable to work with high resolution satellite imagery in an affordable way.

Knowing that the estimation accuracy depends on the variance of the parameter to be measured, further conditions have been defined for this new scheme (to be respected as much as possible):

- To facilitate the implementation of the system, it was decided to use a sampling frame independent of any particular satellite sensor, so that any sensors can be used if suitable to the target; however, observed units may be linked to a particular sensor, considered as best adapted at the date of the survey.
- A preliminary stratification on the forest cover change parameter should be performed to reduce the variance of the estimated variable.
- Unbiased estimators and error variance may be computed from the sample.

METHODOLOGICAL DEVELOPMENTS

Hot Spot Identification

Definition of an Deforestation "Hotness" Index Per Region

Areas of current (1992-1997) deforestation in the moist zone of the tropical belt have been identified by international consultation (Achard *et al.* 1998). The resulting "hot spot" maps and the 1-km resolution forest map are used to stratify the sampling population and to determine sampling rates during the sampling phase.

Deforestation Hotness Index.—In some regions the hot spots cover very large areas (Brazil and Guyanas), while in other regions they cover relatively small areas where deforestation is presumably more concentrated (West Africa and Insular Southeast Asia). To correct for such discrepancies between the heterogeneous sizes of the hot spot areas and their "effective" deforestation rate, a hotness index was defined using the FAO deforestation figures for the period 1990-1995 (FAO 1997). This hotness index is the ratio between the hot spot area of the region and the related deforested area in the period 1990-1995.

$$\text{Hotness}(\text{region}) = \frac{\text{Deforestation } 1990-95(\text{region})}{\text{Hot spot area}(\text{region})}$$

Table 1.—*Deforestation hotness index per region of the tropical belt*

Region	Deforestation 1990-1995 (1000 ha)	Hot spot area of region (1000 ha)	Hotness Index (%)
Central America	4,794	18,400	26.1
Panamazon and Andes	8,764	47,100	18.6
Brazil and Guyana	12,880	112,900	11.4
Continental South-East Asia	5,911	38,300	15.4
Insular South-East Asia	9,401	33,200	28.3
Central Africa	5,699	31,500	18.1
Madagascar	650	6,000	10.8
West Africa	2,459	3,600	68.3

Sampling Scheme

A sampling scheme was developed to address the measurement of the recent forest area changes using high resolution satellite imagery. The statistical sampling will provide an estimate of the precision of the estimator.

Selection of a Sampling Frame

Previous regional or continental monitoring exercises have used the Landsat or SPOT scenes reference systems as a basis for sample unit selection (FAO 1996, Gallego 1998). Such Earth observation satellite-based systems usually locate the remote sensed scenes in a regular manner on the basis of a system of paths (orbits) and rows (arbitrary latitudinal divisions). Such satellite scenes reference systems have the drawback of having overlapping units with an overlap degree that changes with latitude. They can provide a convenient sampling frame around the Equator, but they become increasingly complex polewards. Because the estimation of tropical forest cover change has to be seen in a global context (attention is now being given to Eurasian and North American forests), a system that would be compatible among continents had to be developed.

For this purpose, a sampling frame is constructed that has near-equal area units. The sampling frame is based on hexagon tesselations on a sphere (Thuburn 1997, White *et al.* 1998). The basic geometry can be visualized by looking at a standard soccer ball. Various polyhedral grid systems have been developed for different purposes (White *et al.* 1992, Olsen *et al.* 1998).

This type of geometry has a number of useful characteristics, particularly that the sample frame is made up of nominally equal area and equal shape units, which share a consistent spatial topology with their neighbors. As a result of this, the units all fit together and there are no overlaps or gaps between them. A scheme with equal probabilities of sample unit selection can therefore be devised.

The average size of the hexagons has been tuned to 3,600 km^2, which is comparable to the size of the smallest satellite images (SPOT images are approximately 60 x 60 km). The sampling frame is a finite set of 12,532 points, which are the centers of the hexagons that intersect with the study area by more than 10 km^2. The sampling probability is proportional to the area of the intersection of the hexagon with the study area

Stratification of the Sampling Frame

Stratification reduce the varia of the estimate variable usedin the procedure (forest fragmentation, ecophysiographic units etc.). The absence of adequate maps of forest cover change is a major limitation in producing a good stratification. The hot spot map produced by the expert consultation (Achard *et al.* 1998) ha been used for the stratification. Five strata have been defined (table 2).

The only limitation of the somewhat "subjective stratification" (the hot spot map is derived from individual expertise) is that the estimate of the variances is not as good as when derived from an optimal stratification (i.e., the sampling error is higher).

Eight regions have been identified as areas of particular interest and are used to tune the sample size in each region. The distribution of the sampling frame by strata and subcontinent is given in table 3. The three main strata are stratum 5 (non-forest), stratum 4 (forest without hot spot), and stratum 1 (hot spot area percentage > 50 percent in forest domain).

Table 2.—*Definition of the sampling strata*

		% hot spot area in sampling unit			
		No hot spot	<20%	20-50%	>50%
Percent Forest cover (AVHRR) in sampling unit	No forest (0%)	**Stratum 5**			
	<10%		**Stratum 3**		
	>10%	**Stratum 4**	**Stratum 3**	**Stratum 2**	**Stratum 1**

Table 3.—*Distribution of the sampling frame by strata*

Region	Strata 1	2	3	4	5	Total
Central America	48	38	50	351	164	651
Panamazon and Andes	143	54	98	963	347	1,605
Brazil and Guyana	363	64	77	998	367	1,869
Continental South-East Asia	129	55	90	414	1,273	1,961
Insular South-East Asia	124	50	53	1,038	324	1,589
Central Africa	103	50	62	737	491	1,443
Madagascar	46	2	35	7	153	243
West Africa	10	2	12	168	563	755
Other Regions	0	0	1	320	2,095	2,416
Total	966	315	478	4,996	5,777	12,532

Systematic Sampling by Points on a Regular Grid

A systematic sample of points is based on a rectangular grid in an equal area projection with several replicates. A hexagon is selected if a point of the sampling grid falls inside the hexagon and inside the study area. This provides us with a way of sampling the hexagons of the tesselation with a probability proportional to the area of the hexagon that falls inside the study area. The steps for sampling are:

- Select the equal area projection and the sampling grid. We have chosen the Lambert Cylindrical equal area projection and a grid of 600 km x 500 km.
- Select a pattern of points in the grid cell, which we shall repeat across the grid. We have selected 12 points that will generate 12 replicates. Figure 1 gives the location of the points that generate the six first replicates, for which the replicate number is given randomly.

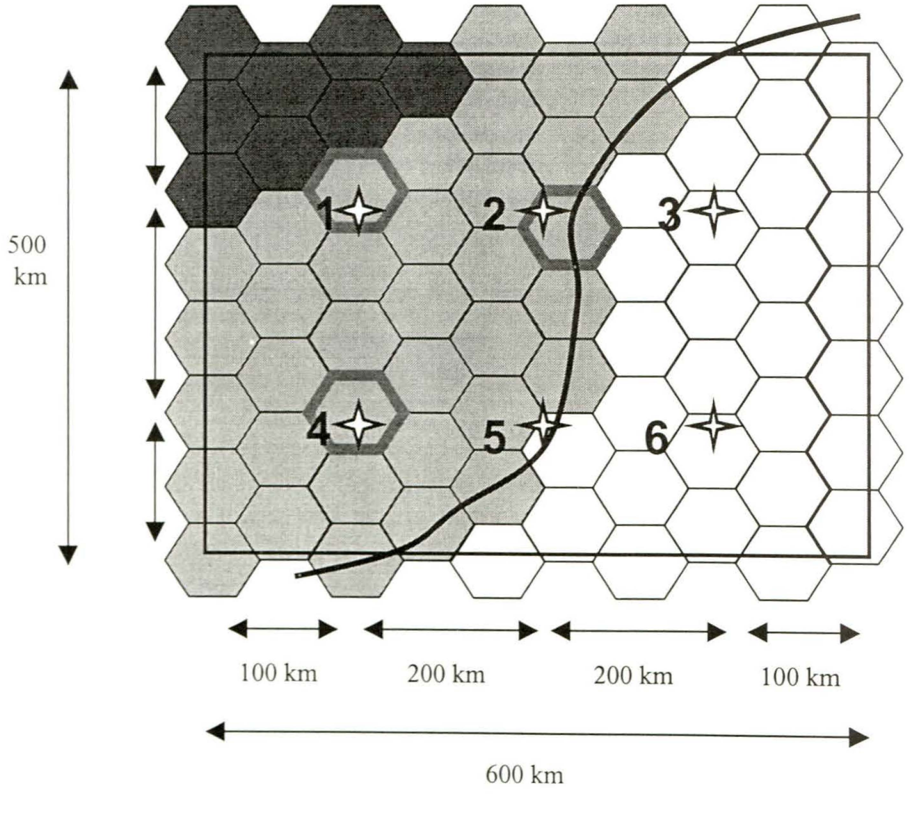


Figure 1.—*Systematic sampling grid with an example of six replicates.*

- Decide the number of replicates that will be kept for each stratum and region. This determines the sampling intensity. The number of replicates per region and stratum have been tuned to be roughly proportional to the hotness index (per region) and with an increasing intensity for hot spot areas (per stratum): see table 4.
- Repeat the pattern of points across the study area for a pre-sample of hexagons. Each point of the pre-sample will be labeled with a number of replicate k.
- If the point k falls in a hexagon that belongs to stratum h and region g, the hexagon is selected if $k \le m_{hg}$, where m_{hg} is the number of replicates for stratum h and region g. When $m_{hg} = 0.5$ (or $m_{hg} = 0.25$), it means that every other (or every four) rectangular grid is used.
- The total target sample size has been set to 95 (as a feasible target linked to availability of resources). A final linear tune of all replicate numbers was made to accommodate that latest figure.

The resulting number of sampling units per stratum and region is given in table 5.

Location and Size of Observation Units

Analysis performed on forest maps for Eurasia suggest that the optimal (in terms of information/ cost ratio) size of observation units (sites) is not the same everywhere. The analysis was based on the comparison between use of full Landsat –TM scene (180 x 180 km) and quarter Landsat –TM scene (90 x 90 km) with the hypothesis that image acquisition and interpretation costs for a full TM scene are about twice the costs for a quarter TM scene. Smaller sites are suitable for relatively homogeneous areas (high spatial correlation), and larger sites are preferable for more heterogeneous areas (Gallego *et al.* 1998).

Table 4.—*Number of replicates per stratum in each region (sampling intensity)*

Region (g)	Hotness Index	Number of replicates per strata (h) 1	2	3	4	5
Central America	26.1	6	3	2	0.5	0.25
Panamazon and Andes	18.6	6	3	2	0.5	0.25
Brazil and Guyana	11.4	3	2	2	0.5	0.25
Continental South-East Asia	15.4	6	3	2	0.5	0.25
Insular South-East Asia	28.3	6	3	2	0.5	0.25
Central Africa	18.1	6	3	2	0.5	0.25
Madagascar	10.8	3	2	1	0	0
West Africa	68.3	12	6	4	2	0.25
Other Regions		0	0	0	0	0

Table 5.—*Number of sampling units per stratum / region /size*

Region	Total per Region (F/Q)	Number of sampling units per strata (Full/Quarter) 1	2	3	4	5
Central America	1/5	0/3	0/0	0/0	1/1	0/1
Panamazon and Andes	7/15	4/8	1/1	0/2	2/3	0/1
Brazil and Guyana	8/12	8/5	0/1	0/1	0/4	0/1
Continental South-East Asia	6/9	4/5	1/1	1/0	0/3	0/0
Insular South-East Asia	7/6	7/1	0/1	0/0	0/4	0/0
Central Africa	9/5	4/0	1/3	2/0	2/2	0/0
Madagascar	0/2	0/1	0/0	0/0	0/0	0/1
West Africa	1/2	0/0	0/0	1/0	0/2	0/0
Total per strata	39/56	27/23	3/7	4/3	5/19	0/4

The information presently available is insufficient to measure spatial heterogeneity of deforestation patterns. We adopted a site size rule based on two assumptions:

- Deforestation will be more heterogeneous where the forest pattern is more heterogeneous;
- Deforestation is more heterogeneous in hot spots.

We consider first the Landsat scenes that have centers closest to the centers of the sampled hexagons. Each selected full Landsat scene *j* defines a cluster T_j of hexagons, for which the Landsat scene center is closest to their centers. The rule selects a full Landsat scene if one of the two following conditions is valid:

- (hot spot area of T_j) x (hotness index of the region) > 250,000 ha
- (standard deviation of forest percent in hexagons within cluster T_j) x (total area of T_j) > 600,000 ha

Otherwise, a quarter Landsat scene is selected, again with a criterion of minimal distance between the center of the hexagon and the center of the quarter Landsat scene. Thresholds for the site size rule were selected after plotting both composite parameters to get a rough proportion of one full scene for two quarter scenes.

Once the sampling scheme is applied, the full or quarter Landsat scenes associated with the sampled hexagons are selected as observational units. The resulting number of full and quarter scenes is given in table 5.

Note the size of the grid cells (600 km x 500 km) and the maximum number of replicates within cells have been selected to ensure that an observational unit will not be selected twice, i.e. than no more than one hexagon in a given cluster is selected.

DISCUSSION ON THE NEW SAMPLING SCHEME

Implementation

This new sampling scheme has been developed to estimate the forest change from interpretations of high resolution satellite imagery in an affordable way. The scheme has to be tested now against implementation constraints such as data availability (partial or total absence).

The non-forest area will be sampled with a very small rate (four sampling units). Images will be acquired for sites with zero percent forest only on specific sample units when there is a doubt on that figure. Otherwise, they will generate a zero value for estimation.

To tackle the issue of non-availability of satellite imagery (for example, in the case of permanent cloud cover), a list of additional replicates can be produced (by increasing the number of replicates in table 4) to allow replacement of missing scenes. The selection should follow a random ranking list within the corresponding stratum. The original sample will remain in the list as missing data.

In some cases, it will be necessary or preferable to reduce the size of the observation units:

(a) because of missing good quality imagery over large areas (cloud coverage)
(b) because existing knowledge would allow replacement of a full scene by one or two quarter scenes (homogeneity of the parameter)
(c) because of the need for higher resolution data for more accurate change measurement (SPOT imagery).

The effect is that data will be partially missing. In case (b), a prediction is used instead of a full measurement. In all cases, the replacing scene should be centered on the original scene location and with the largest overlap.

A simple method for interpretation of the imagery is being developed. Some complex or non-standard aspects can be accepted for the pre-processing level, as long as they are transparent for the final change matrices.

Estimation

In the estimation phase, the selection probability of an observation unit will be taken into account. Applying the site size rule, for each hexagon there is a linked observation unit (full Landsat scene or quarter Landsat scene) and a relative cluster T_j of hexagons. The probability that a specific observation unit is selected is the sum of probability that the corresponding hexagons are selected. Each observation unit does not belong necessarily to a single sampling stratum, but its sampling probability is known. This is a situation of unequal probability sampling rather than stratified sampling.

ACKNOWLEDGMENTS

The authors would like to thank Anthony R. Olsen, U.S. Environmental Protection Agency, Corvallis, OR, USA, for his review of the paper and his very helpful comments.

LITERATURE CITED

Achard, F.; Eva, H.; Glinni, A.; Mayaux, P.; Richards, T.; Stibig, H.J. 1998. Identification of deforestation hot spot areas in the humid tropics. Luxembourg: European Commission. TREES Series B, N°4, EUR 18079 EN. 100 p.

D'Souza, G.; Malingreau, J.P. 1994. NOAA-AVHRR studies of vegetation characteristics and deforestation mapping in the Amazon Basin. Remote Sensing Reviews. Vol.10: 5-35.

Eva, H.D.; D'Souza, G.; Malingreau, J.P. 1995. Potential of ATSR-1 data for detection of clearings within dense humid tropical forest. International Journal of Remote Sensing. 16: 2071-2079.

FAO. 1996. FRA 1990: Survey of tropical forest cover and study of change processes. Rome: FAO, Forestry Paper 130. 152 p.

FAO. 1997. State of the world's forests - 1997. Rome: FAO. 200 p.

Gallego, F.J. 1998. Double sampling for area estimation and map accuracy assessment. In: Mowrer, H.T.; Congalton, R.G., ed. Quantifying spatial uncertainty in natural resources: theory and applications for GIS and remote sensing. Chelsea, MI: Ann Arbor Press.

Gallego, F.J.; Feunette, I.; Carfagna, E. 1998. Optimising the size of sampling units in an area frame. In: Proceedings of GeoENV 98; Valencia; 1998 November 18-20.

Jeanjean, H.; Achard, F. 1997. A new approach for tropical forest area monitoring using multiple resolution data. International Journal of Remote Sensing. 18: 2455-2461.

Lambin, E.F.; Ehrlich, D. 1997. The identification of tropical deforestation fronts at broad spatial scales. International Journal of Remote Sensing. 18: 3551-3568.

Malingreau, J.P.; Achard, F.; D'Souza, G.; Stibig, H.J.; D'Souza, J.; Estreguil, C.; Eva, H. 1995. AVHRR for global tropical forest monitoring: the lessons of the TREES Project. Remote Sensing Reviews. 12: 29-40.

Mayaux, P.; Lambin, E.; 1995. Estimation of tropical forest area from coarse spatial resolution data: a two-step correction function for proportional errors due to spatial aggregation. Remote Sensing of Environment. 53: 1-16.

Mayaux, P.; Achard, F.; Malingreau, J.P. 1998. Global tropical forest area measurements derived from coarse resolution maps at a global level: a comparison with other approaches. Environmental Conservation. 25 (1): 37-52.

Mayaux, P.; Janodet, E.; Blair-Myers, C.M.; Legeay-Janvier, P. 1997. Vegetation Map of Central Africa, Scale 1/5M. TREES Publications Series D, N°1, EUR 17322. Luxembourg: European Commission.

Myers N. 1993. Tropical forests: the main deforestation fronts. Environmental Conservation. 20: 9-16.

Olsen, A.R.; Stevens, D.L.; White, D. 1998. Application of global grids in environmental sampling. Computing Science and Statistics. in press.

Stone, T.A.; Schlesinger, P.; Houghton, R.A.; Woodwell, G.M. 1994. A map of the vegetation of sSouth America based on satellite imagery. Photographic Engineering and Remote Sensing. 60: 541-551.

Thuburn, J. 1997. A PC-based shallow water model on a hexagonal icosahedral grid. Monthly Weather Review. 125: 2328-2347.

Woodcock, C.E.; Strahler A.H. 1987. The factor of scale in remote sensin. Remote Sensing of Environment. 21: 311-332.

White, D.; Kimerling, J.; Overton, W. 1992. Cartographic and geometric components of a global sampling design for environmental monitoring. Cartography and Geographic Information Systems. 19: 1, 5-22.

White, D.; Kimerling, A.J.; Sahr, K.; Song, L. 1998. Comparing area and shape distortion on polyhedral-based recursive partitions of the sphere. International Journal of Geographical Information Systems. in press.

Assessing Change in Large-Scale Forest Area by Visually Interpreting Landsat Images

Jerry D. Greer, Frederick P. Weber, and Raymond L. Czaplewski

Abstract.—As part of the Forest Resources Assessment 1990, the Food and Agriculture Organization of the United Nations visually interpreted a stratified random sample of 117 Landsat scenes to estimate global status and change in tropical forest area. Images from 1980 and 1990 were interpreted by a group of widely experienced technical people in many different tropical countries. The project demonstrated that visual interpretation could reliably quantify broad-scale changes in tropical forest cover and that the procedure was cost-effective, timely, and statistically sound. In 1997, we used the same methodology to interpret and compare Landsat images from two different dates at two sites in the United States to evaluate the methodology's use in northern boreal and temperate forests. We found that the techniques do work in temperate forests and with care can be applied to determining changes over vast areas in northern latitude forests. Here we review the purpose of our pilot test, the methodology used, our findings, and our recommendations. We specifically look at and review the applicability of the classes of vegetation cover used in the tropical assessment and find that, for the most part, they do apply to northern latitudes. We review problems experienced in our effort and present recommendations for preventing these in the future.

The United Nations will coordinate the Forest Resources Assessment 2000 (FRA 2000) to describe the global status of forest resources for the year 2000 and to quantify changes since 1980. Achieving this goal will require: (1) an assessment based on existing national information, complemented by (2) an assessment based on new multidate satellite data in the framework of a global survey design. The United Nations Food and Agriculture Organization (FAO) in Geneva is responsible for collecting existing information and assessing forest trends in industrialized countries (Davis 1997). The FAO in Rome is responsible for assessing forest change and trends in developing countries, using both of these assessment approaches, and for producing the global synthesis.

FRA 2000 was formulated in accordance with the 1992 United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro, Brazil, Agenda 21, Chapter 11, Programme D under the heading "Basis for Action." Chapter 11 describes the present situation of forest resources assessments as follows:

> "Assessment and periodical evaluations are essential components of long term planning, for evaluating effects, quantitatively and qualitatively, and for rectifying inadequacies. This mechanism is, however, one of the often neglected aspects of forest resource management, conservation and development. In many cases, even the basic information related to the area and type of forests, existing potential and volume of harvest, etc. is lacking." (Davis 1997)

To address these concerns, the United Nations Committee on Forestry designed a comprehensive Forest Resources Assessment (FRA) program that has four separate objectives. Our effort was a part of the fourth objective:

> "Remote sensing survey. Includes actions aimed at surveying forest resources state and change at global, regional, and sub-regional levels using remote sensing and statistical sampling." (Davis 1997)

Experts in forest resources from member countries of the United Nations, international and national organizations, non-governmental organizations, and individuals contributed to planning FRA 2000. The international forestry community provided important recommendations through a number of meetings, culminating with the "Expert Consultation on Global Forest Resources Assessment 2000" (Kotka III) held in Kotka, Finland, in 1996. Kotka III recommended expanding the FRA 1990 survey of tropical forests into the temperate and boreal regions to ensure comprehensive and consistent information on forest-related change processes throughout the world. A FRA 2000 strategic plan was developed that provides the

---

Forester, Retired, Consultant to the USDA Forest Service, Remote Sensing Applications Center, McCall, ID, USA; Consultant for Space Imaging EOSAT, Anacortes, WA, USA; and Project Leader, USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO, USA, respectively.

overall conceptual framework for the assessment. In February 1997, the Fourth Session of the UN Intergovernmental Panel on Forests (IPF IV) expressed strong support for FRA 2000, the Kotka III recommendations, and FAO's role as facilitator for the execution of FRA 2000. In March 1997, the United Nations Committee on Forestry endorsed Forest Resources Assessment as one of the highest priorities for the FAO Forestry Department.

In 1997, Mr. Robert Davis, Officer-in-Charge, FRA 2000, FAO, Rome, sent a request to Mr. Doug Kneeland of the International Forestry Program Staff, USDA Forest Service, for assistance from the Forest Service to help assess the procedures to be used in the temperate and boreal forests of the Northern Hemisphere. To meet this need, Czaplewski proposed a project under the coordination of the North America Forest Commission. The purpose of this pilot study, an initial step in that program, was to see if we could use photo interpretation methods on Landsat Thematic Mapper imagery to assess the trend in forest cover in temperate and boreal forests using the earlier FRA 1990 methodology, which was designed for the tropics (FAO 1996). Czaplewski asked Greer and Weber to determine if the methodology and the tropical land cover classification categories would be applicable to the temperate and boreal forests of the United States and to suggest changes that might be needed.

Global land cover can be mapped with low-resolution satellite data (e.g., AVHRR). However, AVHRR data cannot discriminate between many types of forest and land cover, and are not well suited for change detection. High-resolution satellite data (e.g., Landsat, IRS, SPOT, IKONOS) can distinguish between more detailed categories of land cover and can better detect changes in land cover. However, there is no funding available to interpret the thousands of high-resolution satellite scenes that cover each continent. As a compromise, a scientifically valid statistical sample of high-resolution scenes (e.g., 10 percent sample by area) can efficiently estimate the results that would be obtained with the full set of satellite scenes. Cost-effectiveness can be improved by intensifying the sample of satellite scenes within strata that have high priority for assessments or fast rates of change (i.e., "hot-spots") and decreasing the sampling intensity in geographic areas with lower priority. In addition, some results from interpretation of high-resolution satellite data can be predicted from low-resolution satellite data, such as AVHRR and MODIS. These predictions can approximate the results that would have been obtained from an analysis of 100 percent of the high-resolution satellite scenes. This improves monitoring through use of multiple sensor systems.

As part of the FRA in 1990, the FAO in Rome coordinated an effort to visually interpret a stratified random sample of 117 Landsat scenes in developing countries. The objective was to estimate the global status of, and change in, tropical forest areas (FAO 1996, Brown and Czaplewski 1997). Images from 1980 and 1990 were interpreted and compared by a group of widely experienced technical people in many different tropical countries. They quantified areas for nine land-cover classes (four forest classes and five non-forest classes) and the class-to-class changes between 1980 and 1990 in the form of transition matrices. (The results and methods are fully reviewed in FAO 1996.)

FRA 1990 demonstrated that the visual interpretation of digital satellite data could reliably quantify broad-scale changes in tropical forest cover and that the procedure was cost-effective, timely, and statistically sound. Our pilot study tested the applicability of the FAO procedures to classify and compare images from two dates. Specifically, we looked at the methodology and at the vegetative and other categories used in the classification process. We did not carry out the process to statistically evaluate or quantify any change in forest cover in the study areas. This work is a preliminary step before a formal pilot study that would systematically sample and evaluate scenes over a variety of sites in the continental United States and Alaska.

PILOT AREAS

Landsat thematic mapper imagery of an area in southeastern Missouri (central USA) and an area in northern New Hampshire and Vermont (northeastern USA) was furnished to the interpreters. These areas were chosen as representative of some of the mixes of forest vegetation, land uses, and forested landscapes that would be found in the North American temperate forests. Since we were looking at the methodology and at the applicability of classes, there was no need to select test sites at random. Therefore, readily available images of sites were used.

The first set of images covers an extensive area in the southeast quadrant of the State of Missouri. This is a predominately rural area of extensive hardwood forests intermixed with natural stands and plantations of southern pine. Although the area is not heavily inhabited, significant transportation and utility corridors and several communities exist. The terrain has rough, rocky hills with locally steep terrain. This part of Missouri appears to be about 80 percent forested, and agricultural uses are generally limited to more level areas in the floodplains. During the 1920 to 1940 era, many forested areas were cleared for family-based agricultural use, but much of the land is not highly productive. There is limited urban development. Small towns are expanding very slowly, if at all, into the surrounding countryside, and the rural population is not increasing at a high rate. The Mark

Twain National Forest holds large blocks of public land. Private lands are owned primarily by families in comparatively small holdings. Few significant differences are apparent between the images from the two acquisition dates. Road and utility corridor patterns are quite similar on both images.

The second set of images covers an extensive forested area in the northeastern United States. This too is a predominately rural area of extensive forested lands in mountainous terrain. This area in northern New Hampshire and Vermont is generally characterized as a northern hardwood-spruce forest type. The test area embraces a diverse land-use pattern that is greatly influenced by mountainous terrain bisected by streams, major rivers, and large impounded water bodies. The land area of the White Mountain National Forest is a dominant unit of the area. This may account for a measure of stability with regards to change and development within the area. Compared to the Missouri scenes, there were more apparent changes in the landscape on these northeastern scenes. Many recreation homes and condominiums, many associated with large ski area developments, were constructed between the two image aquisition dates. Very little evidence of logging disturbance was observed. There was little evidence of new road construction and development of new utility corridors during the period or of significant expansion of agriculture either in the non-forested areas or as encroachment into forest land. The reversion of agricultural land to forest land and the conversion of fields to forest plantations appear to be a minor influence on land use. The most obvious change during the 1985 to 1996 period was growth and expansion of urban areas into landscapes adjacent to small towns and larger cities.

METHODS

The methodology we tested for this application is taken from the FAO publication *Forest Resources Assessment 1990; Survey of Tropical Forest Cover and Study of Change Processes* (FAO 1996). This publication is based on the work of Rudi Drigo, who developed the technical specifications for the interpretation process.

The Images

The Missouri Landsat scene prints are standard production products. The data set is displayed as a false color infrared representation. The images were acquired in August 1982 and August 1989 and show a large part of the Mark Twain National Forest. The scenes are located at Path 24, Row 34.

The northern New Hampshire and Vermont scenes were acquired in September 1985 and August 1996. The scenes are located at Path 13, Row 29. The prints were produced with an unknown mix of Landsat bands 3, 4, and 5 in proportions that resulted in an atypical overall color. This resulted in a somewhat perplexing fire-like color portrayal of the scene. Also, there is little similarity in the color display between the two dates, and the two scenes are vastly dissimilar in appearance. The 1985 scene is best described as flame orange and the 1996 scene as fall aspen yellow. In work we have supported over the previous 25 years, we have become accustomed to working with the more conventional false color portrayal as in the Missouri scenes.

For each area, we had four prints, each measuring 61 by 61 cm (24 by 24 inches). Two full scenes, one from the early date and one from the later date, provide a broad area reference. The other two prints are quarter scenes, one of the early date and the second of the later date. These prints are of the southeast quadrant. We interpreted only the quarter scenes.

Our interpretation of the scenes was plotted on Plotlar 2000C™—clear, aqueous, coated film. We used fine tip black Pilot™ pens to draw the polygons and pens of a contrasting color to mark reference features for later use in the manual co-registration process. During this pilot test, we did not strictly adhere to the exact technical specifications for materials outlined in the FAO methodology. We used the prescribed minimum mapping unit, which at the proper scale of imagery was described as a square 3 by 3 mm, or a strip at least 2 mm wide for rivers and other linear features.

Delineating the Study Area

Our first step was to delineate the study area for change detection. This is the area on the later date, southeast quadrant image that is fully covered by the earlier date image. Since repeat coverage by satellites does not exactly match earlier ground footprints, we identified the part of the scene that is common to both scenes. The boundary of this area was plotted on a mylar sheet firmly taped to the later date image. Change detection interpretations were made only of the common area. We were not confronted with the case where two sequential early date images may be required to identify a common area of sufficient size on the later date image.

Familiarization with the Study Area

Our next step was to familiarize ourselves with the resultant study area. This included a detailed visual survey of the images to note the locations of clouds and the distribution of forests, farms, and communities. The images were compared to maps of the area and other sources of information about the area that would help the interpreter understand the nature of the area. Greer had lived in the area of Missouri being studied, had attended forestry summer camp there, and had worked in areas of similar vegetative cover. Weber had traveled extensively in the area covered by the northeast scene and had participated in several interpretation projects there. Other sources such as *Bailey's Ecosystem Geography* (Bailey 1996) were used to relate to the rest of the temperate and boreal forests in the Northern Hemisphere.

Assessing Image Quality

With respect to the early date image, we assessed the relative interpretability of each land-cover class. We assessed the level of reliability of its potential delineation into polygons and the likelihood of separating each from adjacent, possibly very similar, classes. As Drigo has pointed out, the accuracy of the interpretation depends upon two main factors. The first factor is the overall quality of the Landsat image, including relative clarity of the print, the contrast, and the nature of the original data acquired by the satellite. The second factor is the interpreter's knowledge of the area being studied and an understanding of the pattern, proximity, texture, and color of the various land-cover classes that might be found within the study area.

Classification of Woody Vegetation and Other Classes

The main classes are the minimum level of classification for the change detection part of the assessment. The additional classes are to be used for change detection only if they may be delineated reliably on both the early date and later date images.

Basically, the photo interpreter identifies and classifies all land cover within the common area on the later date image. The first step is to identify the main categories and delineate primary polygon boundaries. Next, these main classifications are subdivided into the additional classes if their identification is considered reliable. If not, the main class polygons stand on their own.

Interpretation Key

Our interpreted classification test was based on the interpretation key in Annex IIb from *Forest Resources Assessment 1990 Project Monitoring Methodology* (FAO 1991). The classification coding key, from Annex Ia, is reproduced in table 1. It is important to note that this classification scheme was developed initially for tropical areas. Rudi Drigo originally proposed that the temperate/boreal classification be developed on the same concept as the classification system for tropical forests to maximize consistency for global assessments. At issue is whether the classes as described are applicable to the temperate and boreal forests of developed nations and if they fit the needs of developing, non-tropical nations. The initial

Table 1.—*Sampling unit descriptions and classification codes for Forest Resource Assessment 1990* (FAO 1991)

Main classes	Additional classes	Classification codes	
		Main classes	Additional classes
Other land cover		0	
	Snowcaps, rocky area		77
Water		1	
Manmade woody vegetation cover		2	
	Forest plantations		22
	Agricultural plantations		23
Shrubs		3	
	Sparse shrubs (crown cover 10-40%)		33
	Dense shrubs (crown cover > 40%)		34
Fragmented forest		4	
	Forest fraction 10-40%		44
	Forest fraction 40-70%		45
Open canopy forest (Crown cover 10-40%)		5	
Closed canopy forest (Crown cover >40%)		6	
	Closed forest (crown cover 40-70%)		66
	Closed forest (crown cover >70%)		67
Agriculture impact - short fallow		7	
Agriculture impact - long fallow		8	
Other non-interpreted (clouds, shadows, other)		9	
	Burnt woodland		96
	Clouds, cloud shadows		97
	Mountain shadow		98
	Outside study area		99

scheme was designed to provide classes of all types of woody vegetation that might be identified on high-resolution satellite images. These are the categories we used in our pilot study.

An attempt to classify **manmade woody vegetation cover** in contrast to natural woody vegetation cover is made because of a perceived need to analyze and monitor changes in their occurrence and impact on the local forest resource. Even though the classification process is complicated by poor-quality plantations scattered in natural forested areas, the approximate identification of this class is deemed important in tropical areas.

Most of these classes are self-descriptive, but a couple require a clarifying comment. The main classes labeled **agriculture impact - short fallow** and **agriculture impact - long fallow** refer to the practice of clearing small patches of forest land for crops and the shifting pattern that results as patches are farmed, left fallow, and then allowed to revert to forest cover. In the tropics, these patches may be seen in digital images as a sort of mosaic of cultivated areas adjacent to others of similar size in various stages of regrowth.

Interpreting the Later Date Image

We next interpreted the later date image, working within the common area we previously identified. We identified polygons and marked them on the film overlays. This was done to a level at which we felt a difference was reliably recognizable. This is a personal judgment based on the interpreter's experience, knowledge of the area, and quality of the image.

We also marked directly on the overlay the alignment of some rivers, highways, powerlines and other features that would help later to compare the polygons to the earlier date image. When drawing in such identifying features, we periodically placed the early date image under the mylar to see how much information we would need to ensure positive identification of polygons. There are so many roads and features in a developed nation that the overlay can be easily cluttered if the FAO instructions are followed to the letter and all features are identified. As a result, we did not delineate many features (especially rivers) because they were not needed for reference.

Interdependent Interpretation of the Older Image

The second step in the interpretation phase to determine changes in land cover is to interpret the early date image. We followed the Drigo procedure as outlined in *Forest Resources Assessment 1990 Project Monitoring Methodology* (FAO 1991), which is the basis of the following paragraphs. Figure 1 illustrates this procedure.

In this process, we interpreted the early date image with constant reference to our interpretation of the later date image by placing the later overlay over the early image. The rivers, roads, powerlines, and other features that we identified for this purpose were used to align the overlay with the early date image. Then, on top of the later date overlay, we placed a clean early date overlay. We proceeded to redraw the same class polygon boundaries where it was unquestionably clear that no change had taken place. Where the polygon boundaries did not fit, we rechecked the later date image to assure ourselves that our initial interpretation was either accurate or that we had made a mistake. Errors on the later date image overlay were corrected at that time. If our interpretation was accurate, then we delineated the new class boundary and entered the class code only on that portion of the polygon that had changed. Where no changes were found, the class code for the later date image was accepted as the correct one.

In the case of image distortion due to projection, satellite orbital position, or slight differences in scale, we moved and shifted the early date image to align obvious control points and features so that polygons could be compared. Such manual co-registering permits a quick and relatively reliable system for correcting problems without the need to digitize the entire data set into a geographic information system.

Early date images are sometimes of a poorer quality than later date images, and interpreters are reminded in the protocol to be aware of subclasses easily identified on the later date images that will not be seen on the early date images. In cases where subclasses could be identified on later date images but not on early date images, we classified the area to the main class only and dropped all reference to the subclasses.

LIMITS ON THE STUDY

We feel it is important here to note that there was no field verification of any of our interpretations. This is not uncommon in less developed areas where transportation is not as easy or reliable or where the funding for image interpreters is marginal. We believe that the way we carried out the pilot project is similar to the way it will be done in many parts of the Northern Hemisphere.

It is also important to note that we did not carry the pilot test into any statistical analysis of our findings. Our charge was to test the methodology, evaluate the classes of land cover, and comment on anything we found that should be considered if the process is applied to the temperate and boreal forests of the Northern Hemisphere. Therefore, we do not comment on any data compilation phase or on any subsequent statistical assessment process.

Step 1

Interpretation of 1990 image on a transparent film overlay (1990 overlay).

The interpretation includes the delineation of Land Cover Classes and control features.

Step 2

Insert 1980 image between 1990 image and 1990 overlay. Use the delineated control features to adjust the position of 1980 image to fit the 1990 overlay.

Step 3

Interpret 1980 image (on 1980 overlay) using the delineation on the 1990 overlay as a reference.

Check and constantly adjust the position of the 1980 image with respect to the control features marked on the 1990 overlay.

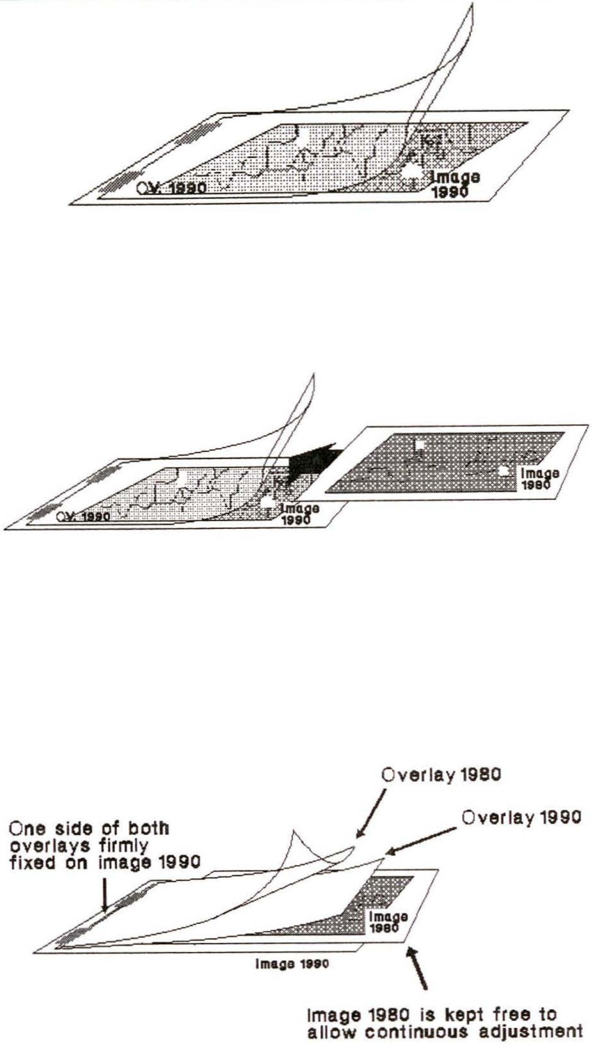

OV. 1990
Image 1990
OV. 1990
Image 1990
Image 1980
Overlay 1980
Overlay 1990
One side of both overlays firmly fixed on image 1990
Image 1980
Image 1990
Image 1980 is kept free to allow continuous adjustment

Figure 1.—*Interdependent interpretation procedure, FRA 1990 (adapted from FAO 1996).*

RESULTS AND DISCUSSION

Image Scale Problems

We had problems with scale on the images as delivered. The scale problem on the Missouri scenes was not apparent, and the interpretation part of the project progressed as planned. The images over New Hampshire and Vermont delivered much later to Weber were obviously off scale. It was only after this discovery that Greer recognized his oversight in not checking the scale of the Missouri scenes upon delivery. The scale problem on the northeast area scenes was corrected before interpretation began. Initially, the two Missouri scenes from the early date and the later date were accurately compared to ensure that both were of the same scale. They were found to be almost identical in scale. The failure to check the actual scale on the Missouri scenes resulted in the use of a template of the minimum mapping unit that was smaller than desired. That template was corrected and all areas near the minimum mapping unit size were rechecked to see if they were still valid. Many were found to not be. This problem can be avoided if every scene is checked for scale upon receipt. Because we were not taking this pilot test into the statistical analysis, the omission was more inconvenient than important. For the FRA 2000 survey, each interpreter should be reminded as a part of the protocol to check and double check the image scale.

Image Color

Our experience over the last 25 years of working with a more conventional false color portrayal leads us to believe that the color infrared format is the best for vegetative interpretation. To experienced photo interpreters, odd or nonstandard color portrayals are usually more of a distraction than a real impairment to interpretation. However, in this case, it was very difficult to manually evaluate changes between two scenes with such wildly divergent and nontypical colors. In any case, scenes for interpretation should be supplied to the interpreter in the format and color commonly used by that person for similar photo interpretation tasks.

Worker Isolation

We feel it is a problem when interpreters work in relative isolation without the stimulation of, and interaction with, others working on the project. We feel that a strong and constant network of communications should be established to share information, problems, encouragement, status, and success. In FRA 2000, this should be recognized because many interpreters across the Northern Hemisphere may be somewhat isolated.

Partial Scenes and the Common Area

Drigo pointed out that the difference between Landsat 1, 2, and 3 orbits and path and row designations may create the need to use two adjacent images of the early date to get a sufficient common area on the later date image. We strongly recommend that when two combined Landsat 1, 2, or 3 images are required for the early date image, the area of interest should be patched in a GIS/Image processor before printing so the interpreter can concentrate on the interpretation task instead of on the technique of getting two images to match the study area as defined by the later date image.

The Interpretation Key

Specifically, the main class "Manmade woody vegetation cover" (and subclasses "Forest Plantations" and "Agricultural plantations") are not discernible on the Landsat images we examined. Someone with a more robust knowledge of local conditions might be able to map some of these classes, but there are no obvious indications on the images. "Manmade woody vegetation cover" and especially "agricultural plantations" seem to be ambiguous. In his review, Gyde Lund agreed. He pointed out that some of the classes are subjective and in some cases call for knowledge of the landowner's or land user's intent. This is especially true of long fallow verses short fallow. Our test certainly supports his point of view. These classification calls require information that is not available from remote sensing data.

"Shrubs" is another category that is not classifiable on our images without an intimate knowledge of local ecosystems. We know from personal experience that shrub fields do occur in southeastern Missouri, specifically oak regrowth, sumac species, eastern red cedar, and other invader species on abandoned farms. Depending upon the species, some of these shrub lands may qualify as some class of forest cover. By definition, forest cover includes lands that are temporarily unstocked as a result of human intervention or natural causes but which are expected to revert to forest (UN-ECE/FAO 1997). Many of these fields are below the minimum classification unit, but large fields do occur. It is not hard to imagine that shrub fields exist on the steep south exposures of many mountain niches in Vermont and New Hampshire, but we were not able to classify any. We have seen and classified shrub fields on Landsat scenes of lands in Colorado, Idaho, and South Dakota, but in almost every case that was supported by detailed local knowledge gained from survey work in these areas.

Perhaps the least applicable classifications in the United States are those associated with "Agricultural Impact." Because of the different system of land ownership and regulation in the USA, we do not normally see either short-fallow or long-fallow agriculture practiced. Therefore, these classes become meaningless in the United States and may be useless in the rest of the developed Northern Hemisphere. This is probably also true within boreal forest areas.

There is one exception to this statement about short-fallow farming of which we are aware. In the tobacco-producing regions of the southeastern United States, it is common practice to prepare a new seedling bed for new tobacco plants each year. These are created on small plots in newly cleared forest cover. Perhaps it is only tradition, but growers prefer to have a newly cleared patch of forest ground for this. These patches are below the minimum mapping unit size and never constitute (in our opinion) a significant impact on the region, but they do represent a short-fallow system in a heavily developed part of the world.

Other non-interpreted subclasses are straightforward except for "Burnt woodland." In some cover types, burned areas will be obvious. Any conifer cover type in either the temperate or boreal forest will probably be obvious if the burn intensity was moderate or high. Low burn intensity and some moderate intensity burned areas will not be evident and cannot be reliably mapped (Greer *et al.* 1996). In deciduous forests, we suspect that only high burn intensity fire areas will be obvious, and even then, it may take some good local knowledge to map some burned areas. As a result, and in our opinion, we will not be able to map any burn areas to meet the definition in the publication *Forest Resources Assessment 1990 Project Monitoring Methodology* (FAO 1991). Code 96 is to be used only in woodland areas where recurrent fires destroy only (or mainly) the grass layer present under the tree cover. By definition, this is a low burn intensity fire and it will not show up in our forests unless the canopies are very open (i.e., crown cover 10 to 40 percent). As a result, this class that normally would be non-interpreted will be interpreted and classified as some other forest cover class. In other locations where fires have destroyed the forest, in other words, moderate to high burn intensity, we can map them as code 0 areas because they become by definition "Other land cover."

We suggest that for analysts working in unfamiliar parts of the world, the single best tool for training and familiarity that can be provided is one good aerial color or color infrared photographic stereo pair, at a relatively large scale such as 1:8000 or larger. We recognize that in most of the world, this is rarely available. However, one good high-resolution, pan-sharpened satellite stereo pair for each sampled scene would be a good substitute to assist and train an analyst in interpretation of Landsat scenes where photography is not available. New multispectral space-based platforms, such as IKONOS 1 & 2, provide 1-m pan-sharpened multispectral data. The information content is comparable to a conventional 1:2,400 RF aerial photograph.

We suggest that time spent in preparing more formal and detailed interpretation keys using samples of imagery to illustrate the classes would provide more consistency of interpretation.

Suggestions for New Subclasses

Obviously the northern temperate and boreal forest differs greatly from that of the tropics. One major difference is the rapidity of development and use of wild lands where forests are converted to other uses. We suggest that subclasses should be developed to reflect the loss or gain of forest areas resulting from such urban development and sprawl. Subclasses for other change agents like geologic processes and climate change should also be developed. If we want to track specific trends, the following subcategories might be helpful.

Urban, where forests are replaced by development.

Reclaimed sea bed, as in Holland where forests may be planted.

Landslides, where in mountains, significant slides can change large areas. This may be important in the Rocky Mountains, the Alps, the Himalayas, and Caucasus.

Glaciers, where forests can come and go as glaciers advance and retreat over long periods of time.

Tundra and permafrost, where forest growth can advance with warming climate.

Ocean/sea, where rising levels encroach on land as a result of global warming and destruction of forests.

Retired pasture, where forests are retaking pasture lands after hundreds of years of use; this may represent an agricultural impact that could be characterized as very long fallow.

Focusing on forest cover alone may cause us to miss an opportunity to evaluate trends on an ecosystem basis. With biodiversity now a major concern, we may want to look at a sampling protocol that will let us monitor shifts of a variety of cover types other than just forests. For example, the extent and distribution of mountain meadows might be a critical forest statistic to monitor.

Opportunities for Cooperative Cost Reduction

Establishing cooperative projects or at least coordinating our efforts with Canada and Mexico with regard to the sampling design could reduce the overall North American costs of FRA 2000.

SUMMARY

We believe that generally, the methodology and classification key developed by Drigo as reported in FAO, 1996, for tropical areas can be used to assess trends in northern boreal and temperate forest cover. There may be some automated procedures utilizing image processing that could be used to support the manual interpretation and classification. It also seems plausible that the work could be concentrated into the hands of a relatively few interpreters located at central processing centers.

In the United States, there are sources of important data not normally used in such projects. National forests, most BLM districts, and national parks in the United States have special "project photography" that is not centrally indexed. These important sources of data, with photo index maps, are usually kept in the Supervisor's, District Manager's, or Superintendent's offices. Other potentially important sources of photographic data such as the Space Shuttle LFC images from 1984 are available. In the near future, civilian, high-resolution, pan-sharpened, multispectral satellite data will be available for reference.

ACKNOWLEDGMENTS

We thank our two peer reviewers, Mr. Rudi Drigo, FAO, United Nations in Rome, Italy, and Mr. H. Gyde Lund, Integrated Resource Inventories and Assessments, Manassas, VA, USA, who took the time to review our drafts. Ms. Rachael Hershey, USDA Forest Service, Northeastern Research Station in Radnor, PA, assisted in image acquisition for New England. Mr. Henry Lachowski, Mr. Paul Ishikawa, and Mr. Mike Hoppus at the USDA Forest Service's Remote Sensing Applications Center in Salt Lake City, UT, assembled the Missouri images and supplies needed for the project. Our French and Spanish title and abstract translations were prepared by Mr. Javier Gallego in Italy.

Much of our review of the FRA 1990 material is paraphrased from the United Nations references cited in the body of this paper. We acknowledge those materials and their unidentified authors as deserving of credit, and we are in no way attempting to take credit for their work in formulating the methodology.

LITERATURE CITED

Bailey, R.G. 1996. Ecosystem geography. New York, NY: Springer. 204 p.

Brown, S; Czaplewski, R.L. 1997. Global information on tropical forests. Science. 277(5328): 883-884.

Davis, R. 1997. Assistance needs from the USDA Forest Service in the execution of the Global Forest Resources Assessment 2000. A proposal from Robert Davis to Doug Kneeland, U.S. Department of Agriculture, Forest Service, International Forestry. Available from Ray Czaplewski via email at this address: rlczaple/rmrs@fs.fed.us

FAO. 1991. Forest Resources Assessment 1990 Project Monitoring Methodology. Field Document FO:GCP/INT/501/FIN. Rome, Italy: Food and Agricultural Organization of the United Nations. 46 p.

FAO. 1996. Forest Resources Assessment 1990; survey of tropical forest cover and study of change processes. For. Pap. 130. Rome, Italy: Food and Agricultural Organization of the United Nations. 152 p.

Greer, J.D.; Ekstrand, R.E.; Coffland, B.; Demetriades, T. Wirth, T. 1996. Wildfire burn-intensity mapping using high-altitude reconnaissance photography. In: Airborne reconnaissance XX; 1996 August 6-7; Denver, CO. Proceedings of SPIE volume 2829: 83-99.

UN-ECE/FAO. 1997. UN-ECE/FAO Temperate and Boreal Forest Resources Assessment 2000 - terms and definitions. GE. 97-22231. Geneva, Switzerland. 13 p.

Change Detection using NALC MSS Triplicates to Set Forest Planning Context

D.R. Grey, P.E. Gessler, M. Hoppus, and S.L. Boudreau

Abstract.—The USDA Forest Service has purchased the North American Landscape Characterization (NALC) Landsat Multispectral Scanner (MSS) triplicates (70's, 80's, and 90's) for every national forest in the United States. To encourage analysis and use of these data for forest planning, a change-detection training course was developed. The course covers basic methods and options for developing change detection maps including visual, post-classification comparison, image algebra, principal components analysis, and unsupervised techniques. The broad spatial and spectral resolutions of the MSS data preclude use of these data for detailed tree species and forest habitat mapping. However, the broad synoptic nature of these data sets, available over a 25-year time period, provides a useful context within which more detailed analyses and management planning can take place.

Change detection is the process of identifying differences in the state of an object or phenomenon by observing it at different times (Singh 1989). Many tools and techniques are available to detect and monitor changes in land-cover and vegetation patterns. These techniques include professional knowledge of the area, sampling techniques, aerial photo interpretation, and digital image processing of satellite or airborne imagery. Digital image processing of remotely sensed data offers the benefits of quantifying change in a format compatible with digital GIS layers. The basic premise in using remote sensing data for change detection is that changes in land cover must result in changes in radiance values, and radiance due to land-cover change must be large with respect to radiance changes caused by other factors (Ingram and Robinson 1981). For example, the change in reflectance resulting from a clearcut must be greater than the differences in atmospheric conditions to successfully detect and interpret the change.

Several methods detect change using remotely sensed imagery. At least nine change-detection algorithms are commonly used (Jensen 1996), including the following:

- change detection using write function memory insertion;
- multi-date composite image change detection (single classification or principal components analysis);
- image algebra change detection (band subtraction or band ratioing);
- post-classification comparison change detection;
- multi-date change detection using a binary mask applied to date 2;
- multi-date change detection using ancillary data source as date 1;
- manual on-screen digitization of change;
- spectral change vector analysis; and
- knowledge-based vision systems for detecting change.

These techniques should be researched carefully prior to implementation, to determine which techniques best fit the needs of the researcher. For example, change output data can be continuous or categorical, and some techniques can use only one band or index at a time while others allow the simultaneous processing of multi–band data sets.

NALC Data Sets –Historically Valuable

The North American Landscape Characterization (NALC) Triplicates are available for the entire United States and parts of Mexico and Canada. The triplicates consist of three coregistered Landsat Multispectral Scanner (MSS) scenes and a composite of 60-m Digital Elevation Models for the area covered by the MSS scenes. The images were processed by the Earth Resources Observation Systems (EROS) Data Center and contain information from each of the past three decades (1973, 1986, and 1991 plus or minus 1 year). These images provide quantitative data on surface reflectance responses useful for evaluating management practices, disturbance, and successional changes over a large area. The images are also a valuable reference for future studies because they serve as an objective record of past patterns.

Research Assistant, Department of Forest Resources, University of Idaho, Moscow, ID, USA; Professor of Remote Sensing, Department of Forest Resources, University of Idaho, Moscow, ID, USA; Analyst, USDA Forest Service, Remote Sensing Applications Center, Salt Lake City, UT, USA; Ecologist, USDA Payette National Forest, McCall, ID, USDA, respectively.

The spatial resolution of acquired MSS data are course at 79 by 58 m. The MSS scenes in the NALC triplicates were resampled at EROS to 60- x 60-m pixels to simplify area and distance calculations and maintain compatibility with other digital data sets (i.e., Thematic Mapper, USGS 30 DEM's). The MSS acquires data in four broad spectral bands over the green, red, and two near infrared portions of the spectrum (0.5-0.6, 0.6-0.7, 0.7-0.8, and 0.8-1.1µm, respectively). The spatial and spectral resolutions of the MSS data are sufficient for evaluating landscape-level vegetation, or land-use changes.

Change Detection Training Course

Many different change-detection algorithms and techniques have been implemented. Muchoney *et al.* (1994) used principal components analysis, unsupervised, image differencing, and post-classification comparison change-detection techniques to monitor forest defoliation. Lyon *et al.* (1998) used image differencing with several vegetation indices to monitor vegetation change. Several change-detection procedures were compared for monitoring eelgrass populations in Great Bay, NH (Macleod *et al.* 1998). Methods incorporated into the change detection training course developed for the USDA Forest Service are:

- change detection using write function memory insertion (WFMI);
- multi-date composite image change detection (single classification or principal components analysis (PCA));
- image algebra change detection (band subtraction or band ratioing);
- post classification comparison (PCC) change detection;
- manual on-screen digitization of change; and
- multi-date composite unsupervised classification incorporating a visual color model change enhancement (UVCM).

Other change-detection techniques exist (Jensen 1996) but were not included in the course.

Unsupervised Classification Incorporating a Visual Color Model

A multi-date composite unsupervised classification incorporating a visual color model change enhancement technique was developed and incorporated into the classification portion of the multi-date composite change-detection portion of the training course. This technique combines the visual change coloring advantages of the WFMI technique, as well as the from-to change categories of classification. UVCM has the additional advantage of providing a means of evaluating the number of classes used prior to labeling classes by comparing the color contrast in the image with the color contrast in the WFMI technique.

METHODS

The change-detection training course developed for the USDA Forest Service integrates techniques most commonly used within the literature. Two dates, July 1974 (fig. 1a) and July 1992 (fig.1c), in the three-date NALC imagery time-series were used for analysis and methodology demonstration. The July 1985 (fig. 1b) image was not used because of significant cloud cover and shadow over the study area.

The study area for the project was the North Fork of the Payette River Watershed, north of McCall, ID (NW corner: 116°07'30", 45°15'; SE corner 115°52'30", 45°15'). This area burned extensively in the summer of 1994. The NALC Triplicates provide a means of evaluating the changes prior to the fire, and a means of comparing the ecological succession on the ground with historical conditions.

Change Detection Using Write Function Memory Insertion

This is a visual technique for exploring change in a two- or three-date composite image data set. First, a band useful for characterizing change is selected. Second, this band is assigned a unique color gun (red, green, and blue) for each date. The images are then displayed on a graphics device. The image will appear as grayscale in areas of no change, and will appear colored where change is present. The order the dates are displayed in the color guns will affect the color output according to additive color theory. The NIR band 4 was selected because it reflects highly in areas of photosynthetically active vegetation. The NIR also has different reflectance/absorption characteristics depending on the moisture level, leaf structure, and leaf age of the vegetation. These characteristics are helpful when evaluating broad vegetation changes as well as when distinguishing vegetated from non-vegetated areas. Because two dates were used in our analysis, NIR band 4 of the July 1992 MSS image was displayed in the red and green color guns and NIR band 4 of the July 1974 image was displayed in the blue color gun. This band combination produces a display where areas with higher brightness values in 1992 appear as shades of yellow, and areas with higher brightness values in 1974 as blue. According to additive color theory, equal intensities of red and green produce yellow where blue values are low, and blue where the values of red and green remain low, constant, and equal.

The output image may be interpreted, compared with, and used to check other techniques for change consistency or misclassification of change areas.

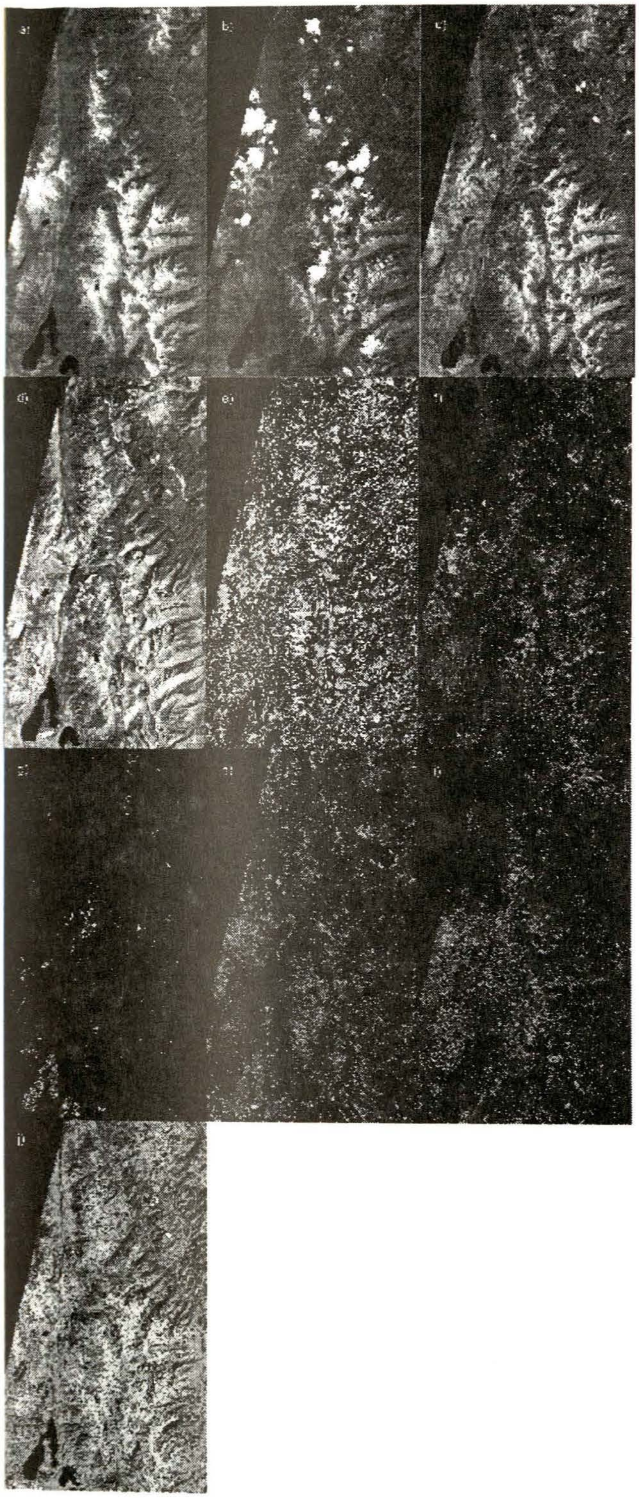


Figure 1.—*July 1974 MSS; b) July 1985 MSS; c) July 1992 MSS; d) Write Function Memory Insertion; e) Post Classification Comparison; f) Band 4 (NIR) Subtraction; g) Band 4 (NIR) Ratio; h) NDVI Subtraction; i) Principal Component analysis; j) Unsupervised Change Detection.*

Post-Classification Comparison

Post-classification comparison is the most commonly used quantitative method of change detection (Jensen 1996). This technique requires a separate classification for each date using the same or similar land-cover classification scheme (i.e., Anderson level II). Post-classification change detection is likely the most straight-forward change-detection process, but it also has the potential for being the least accurate (Macleod 1998). To limit the error in classification and provide consistency between classifications, a classification system based on the Anderson Land Use and Land Cover Classification (levels 1 and 2) System was developed (Anderson *et al.* 1976). The classes included were:

- herbaceous rangeland;
- shrub rangeland/deciduous forest;
- low density evergreen forest;
- medium density evergreen forest;
- high density evergreen forest;
- water;
- rock/mineral soil;
- shadow; and
- clouds.

Aerial photographs taken within a few years of the satellite imagery were used to help define homogeneous land-cover class areas suitable for training sites. Color 1:16,000 photographs taken in July 1976 were used for identifying and delineating training sites for the July 1974 MSS imagery. Color infrared 1:30,000 photographs taken in 1994 were used to define training site and ground truth data for the 1992 MSS imagery. These areas were located on the MSS data and compared with the photos to ensure the pattern was consistent with the photograph. Training sites were then delineated for use in classification.

Digital imagery training site samples for each information class (listed above) were compared (mean, range, standard deviation) and merged into individual spectral response functions. Merged training site histograms that did not approximate a unimodal distribution were discarded except in cases where land-cover types contained high variation. For example, the spectral responses of the rock/mineral soil class contained high variability likely due to differences in rock size, type, and topographic effects (i.e., slope, aspect, shading).

Supervised classification was performed using a parallelepiped decision rule to presort the data into information classes. A maxim likelihood decision rule was then used to assign unclassified pixels and pixels in overlapping classes to a final class. After the classification was implemented, the modified Anderson information classes were assigned to the corresponding spectral clusters in the output image using the aerial photographs for cross-checking. Separate image clusters assigned to the same information class were then recoded into the same image class.

The resulting images were then combined using a matrix GIS operation. Matrix operations combine images on a pixel by pixel basis for comparison of changes. The matrix image contains from-to data important in evaluating change on both an individual pixel basis and in the broader image context. Significant changes of interest, such as conifer high density to shrub rangeland, conifer high density to conifer low density, and conifer medium density to herbaceous rangeland, were then assigned colors for visualization of these changes over the study area.

Image Algebra

Band subtraction and band ratioing are two common methods of image algebra change detection. In band subtraction, spatially registered images of time t_1 and t_2 are subtracted, pixel by pixel, to produce an image that represents the change between two dates (Singh 1989). The subtraction results in positive and negative values in areas of reflectance change and zero or near zero values in areas of no change (Jensen 1996). Band ratioing is the division of image brightness values in date 1 by the brightness values in date 2. The resulting image contains values near 1 in areas of no change and floating point values at change locations. In a ratio operation, values below 1 are compressed, so often two change images must be developed, each emphasizing a different tail in the image histogram.

To emphasize vegetation change, band 4 was used in both the subtraction and ratio techniques. In addition to band 4, a Normalized Difference Vegetation Index (NDVI = (Band 4 - Band 2) / (Band 4 + Band 2)) was used with the subtraction method. Divide-by-zero errors can occur with ratio operations in some software packages. To solve this problem, a pixel value of 1 was added to every pixel in both images before ratio calculation.

Image statistics were used to define change intensity levels. Pixels greater than one standard deviation from either side of the mean were assigned to a standard deviation level. For example, 1.0 to 2.0 standard deviations may serve as an interval. The standard deviation levels may then be assigned colors. A color ramp was used to assign a lighter shade of color to values closer to the mean and a darker shade to values farther from the mean. By applying the individual colors and brightness levels, quantifiable changes may be visualized for each tail of the image histogram.

Multi-date Composite

The multi-date composite change-detection methods demonstrated in the course included principal components analysis (PCA), unsupervised classification, and unsupervised classification incorporating a visual color model change enhancement. To perform these techniques, a multi-date image was first produced by adding all bands from date 1 to date 2 as additional layers. The resulting image contained the 1974 image bands in layers 1 through 4, and the bands from 1992 in layers 4 through 8.

Principal Components Analysis

PCA was performed on the two-date image using the Principal Components utility within *Erdas Imagine 8.3.1*. To interpret the components, a covariance matrix was calculated for each band within the multi-date data set. Standard deviations were also calculated for each band in the data set. The eigenvalues, eigenmatrix, covariance, and standard deviations were output to a spreadsheet to calculate the correlation between the original bands and the PCA components in the output image. The correlation matrix is used to determine if an individual component is related to a specific date band. The image can be interpreted visually by relating the bright pixels within the components to the statistics and photographs. The components were processed further through an Intensity, Hue, and Saturation (IHS) color slice. This separated the differing levels of brightness within the components and aided in exploration of definable changes.

Unsupervised Change Detection

The unsupervised change-detection procedure used an unsupervised classification on the multi-date composite image. If an appropriate number of classes are specified, the output image will capture change classes representing both change and no-change patterns. Because the input images would otherwise be similar, changes differentiate statistically (Weismiller *et al.* 1977). Three classifications with 20, 40, and 75 cluster classes were performed to evaluate the number of clusters needed to capture change in our study area. To ensure that most pixels were assigned to a spectral cluster, the convergence threshold was set to 98 percent and the number of iterations was set to run continuously until the threshold was achieved. Two additional columns, a 1974 class and a 1992 class, were added to the output image attribute file to provide a location for both 1974 and 1992 class names. Aerial photographs from both dates were used to identify land-cover types and assign information classes to the spectral clusters. The Anderson classification, as discussed above, was used as a guide, but additional information was added to account for variation in spectral clusters of similar land-cover classes. For example, conifer forest spectral clusters of equal stand density contained herb, brush, and mineral soil understories. The advantage of this technique is that only a single classification is required; unfortunately, it is often difficult to label the change classes (Jensen 1996). Experimentation with several classifications may be needed to determine the number of cluster classes needed to sufficiently capture change and class variation.

Unsupervised Classification Incorporating a Visual Color Model

A hybrid technique was used to capture the benefits of a categorical from-to structure and the visual change information immediately apparent from change detection using WFMI, and image algebra methods. The multi-date composite unsupervised classification incorporating a visual color model change enhancement technique is essentially the same as the unsupervised change-detection method except that a color model is used to initially color the output change classes by approximating the change coloring of the WFMI method. This was accomplished by using the "Approximate True Color" option in the Unsupervised Classification menu within *Erdas Imagine 8.3.1*. This option assigns an approximated color of a specific band combination to the spectral clusters in the classification. By applying the band combination used in the visual technique (Red = 1992 MSS band 4, Green = 1992 MSS band 4, and Blue = 1974 MSS band 4), change classes were colored in shades of gray, yellow, or blue. The output classified image was then compared to the WFMI technique. The number of spectral clusters used was evaluated by a visual comparison of the color contrast within the colored areas of the WFMI image. It was determined that 75 classes best captured the variation within the change areas.

RESULTS

Differences in the shape and distribution of the 1974 and 1992 image statistics suggested an overall difference between the two images. The July 1974 image contained maximum values much higher than the July 1992 image. Therefore, the mean and standard deviations of the 1974 data set were much different than the 1992 data. The maximum values within the 1974 image are found on the rocky mountain peaks throughout the area. There are two hypotheses to explain these high values. The first is that the peaks were covered with snow at the time of the 1974 imagery. The other is that highly reflective rock surfaces saturated the sensors onboard Landsat 1. If reflective surfaces were saturating the MSS sensor on Landsat 1, change in similar areas may be difficult to quantify. A review of weather data should help determine the cause.

Write Function Memory Insertion

The WFMI technique was very useful for initial identification of change areas and for comparison with changes identified by other techniques (fig. 1d). This method identified change verified by the photographs. It also helped in the identification of change that was not initially apparent in the photographs. Because the areas were highlighted, additional photo interpretation revealed forest thinning and tree mortality. A main advantage to the technique is that the contrast and purity of the colors in the band combination quantify a direction and magnitude of change. Potential limitations of this technique are that all analysis is visual; because the change image is just a band, combination change class information cannot be attached to the image, and change is quantified by reflectance differences in a single band. Changes in different wavelengths must be displayed independently. Although limitations to this technique exist, it is quick, simple to use, and can be implemented by most remote sensing and GIS software packages. It may be implemented as the first change technique applied in a change-detection study. Resource professionals can implement this technique with only basic knowledge of spectral biophysical properties of the land cover and additive color theory.

Post-Classification Comparison

Post classification comparison change detection was performed after a supervised classification of the two dates of imagery (fig. 1e). The information classes used in the classifications matched well when comparing the photographs to the output classified images. Most inconsistencies in the classified imagery were in regions of similar classes. Low- and high-spectral extremes of these classes are where misclassification is most likely to occur. These inconsistencies were greatly enhanced when the two images were combined in the matrix operation. Change between classes such as herbaceous rangeland and open forest, low-density forest and medium-density forest, or high-density forest and medium-density forest was less reliable due to insufficient data to resolve differences between the classes. However, distinct changes such as high-density forest to low-density forest, high-density forest to rangeland, or rangeland to water were very reliable when comparing the change to the photos. Post-classification comparison change detection requires the most time and the most expertise to achieve good classification accuracy. Macleod (1998) states, "the accuracy of the post-classification comparison change-detection technique may be poor because of combining the errors from both of the classifications." Classification errors are also not distributed equally throughout all classes. Change classes that attempt to quantify changes in similar from-to classes will have a much lower accuracy than classes that are more distinct. This classification technique is useful when broad, contextual change detection is desired, but may perform poorly when differentiating changes between similar classes.

Image Algebra

Image algebra change detection provides a rapid output change image. Band ratioing provided the simplest map of change (fig. 1g). This technique requires two separate ratios for each direction of change over the change time-series. The result is two separate images showing areas of increasing or decreasing digital number value changes. The output grayscale images distinctly highlighted major reflectance changes. The use of a standard deviation coloring scheme further enhanced interpretation of major changes. Minor reflectance differences are not as apparent as with band or index subtraction image algebra techniques.

Band Subtraction provided the best compromise between the detection of small reflectance differences and large reflectance differences (fig. 1f). Unlike band ratioing, subtraction images contain areas of both increasing and decreasing radiometric value change. This produces a gradational image that is initially difficult to interpret. After RGB color slices were applied to the standard deviation intervals, change was characterized by the gradations within the standard deviation classes and used to define change thresholds. A final output image may then display both direction and magnitude of radiometric change.

NDVI Subtraction did not perform as well as other methods. The output image showed a large amount of change area when compared with the other techniques (fig. 1h). The application of color slices to the standard deviation levels did little to improve the interpretation of the image. Major known changes appeared as low-level change. We suspect differences in sensor calibration for the different dates and the normalization for the NDVI calculation make it difficult to compare and compute change.

In all image algebra techniques, specific change classes cannot be attached to the image. For example, a cloud shadow to brush change could be represented by the same digital value difference as a dense forest to brush change. Attaching a specific context requires an additional classification of just the changed areas. This can be accomplished by using the thresholded image algebra output image as a mask to erase the unchanged area from the original imagery. The masked images could then be classified and combined in a matrix operation to define a from-to context.

Multi-date Composite

Principal Components Analysis

The differences in image statistics caused problems with the interpretation of the correlation between principal components and bands in the two-date image data set. Specific change was difficult to determine except in areas of significant change (fig. 1i). The outputs of the PCA change detection were difficult to interpret. Good ground truth data would greatly assist in interpretation of outputs.

Unsupervised Change Detection

Unsupervised change detection performed well once a sufficient number of classes were established. The simultaneous interpretation of spectral clusters using aerial photo interpretation for both dates may help limit some of the classification inconsistencies often found in the post-classification comparison technique. The classification accuracy may not be improved over PCC, but classification consistency between two separate classifications is not an issue when using the unsupervised technique. Unsupervised change detection on a multi-date composite image is classified by comparing the aerial photographs with several spectral cluster locations in the image. Post-classification comparison relies on an exclusive and finite number of training sites for classification. Several classifications were needed to determine a sufficient number of spectral clusters for this technique. The time required performing these separate classifications rivaled the time required for Post-classification comparison. The initial number of classes chosen for this technique should be set high to capture the variation in the imagery for each date. Seventy-five clusters were sufficient to detect change in our study area (fig. 1j). The number of classes required may increase with the number of spectral wavelengths represented in the data set and the extent and land-cover complexity of the study area.

Unsupervised Classification Incorporating a Visual Color Model

Multi-date composite unsupervised classification incorporating a visual color model change enhancement technique simplified the identification of change clusters. Evaluation time was greatly reduced over a normal unsupervised classification by comparing the immediate output from the classification algorithm with the WFMI technique (fig. 1d). Because evaluation of the number of classes is aided by the comparison of color contrast in the output image with the WFMI image, assigning information classes is not necessary in the initial class number evaluation. This contributes to substantial time savings over the traditional unsupervised change technique. The number of spectral clusters used in classification was considered acceptable when the color approximations in the classified image closely matched the colors in the visual change-detection technique. The coloring provided an initial change context of high to low and low to high radiance change. This context aided interpretation when assigning information classes to spectral classes in change areas and has the potential to reduce user error.

NALC Triplicates

The NALC triplicates were very successful in identifying human-caused and natural disturbance as well as climatic differences. Vegetation changes due to clearcuts, thinning, fire, insect mortality, and succession were all apparent in the output change images when compared with interpretation of the aerial photographs. Also apparent were water level and snow differences between dates. The specific nature of the change was not identifiable in the MSS imagery, but may be extracted through the use of additional GIS layers, professional knowledge of the area, and field interpretation. This was beyond the scope of our study, but could be a routine add-on for resource professionals working in an individual natural forests.

CONCLUSIONS

Many change-detection techniques exist, and the advantages and disadvantages of each should be considered before the selection of a specific method. Change detection using write function memory insertion was rapid and easy to use. It is useful as a first step because all other change techniques can be compared with this technique to see what kind of change is being detected (increasing or decreasing brightness value change) or where change may be misclassified. The main limitation is that the change detection is visual. Image algebra is also easy to implement but requires the definition of thresholds to identify real change. Many change images can be produced by image algebra using different bands, indices, and operators. The output images can be analyzed using image statistics, but categorical information classes cannot be attached to the image except when combined with a post-classification comparison or other ancillary data. Post-classification comparison is very useful when a from-to context is required. The individual images may be used in combination with GIS layers or future classified images to extract more change information. Drawbacks to this technique are the time involved in producing separate classifications, user error, and the potential to extract more information from the imagery than is spectrally available. Unsupervised classification may require extensive trial and error before an appropriate number of classes are selected. Unfortunately, information classes need to be attached to each trial to evaluate the change classification. Multi-date composite unsupervised classification incorporating a visual color model change enhancement technique provided the best compromise between an image classification and quick identification of change. The approximated color scheme used in the initial output image is very useful for determining a sufficient number of classes when compared to WFMI. The contextual coloring of change also allows for a faster, potentially more accurate classification of change.

The NALC triplicates can sufficiently define broad change. Interpretation of this change will require photo interpretation, ancillary data, and fieldwork data. The large temporal span of the NALC imagery may help the resource manager identify slow changes that are not easily perceived.

The initial choice of a change-detection algorithm should be based on the purpose of the change study and the limitations of the individual techniques. Successful change detection is also dependent on the data used and its limitations. Trying to extract more information from the imagery than the resolutions (spatial, spectral, and temporal) of the imagery may lead to poor accuracy as well as inappropriate change-detection results and interpretations.

LITERATURE CITED

Anderson J.R.; Hardy, E.E.; Roach, J.T.; Witmer, R.E. 1976. Land use land cover classification scheme for use with remote sensor data. Washington, DC: United States Government Printing Office.

Ingram, J.P.; Robinson, J.W. 1981. Change detection technique development for improved urbanized area delineation. Technical Mem. CSC/TM-81/6087. Silver Springs, MD: Computer Sciences Corporation.

Jensen, John R. 1996. Introductory digital image processing. 2nd ed. Upper Saddle River, NJ: Prentice Hall.

Lyon, J.G.; Yuan, D.; Elvidge, C.D. 1998. A change detection experiment using vegetation indices. Photogrametric Engineering and Remote Sensing. 64(2): 143.

Macleod, Robb; Russell, D.; Congalton, G. 1998. A quantitative comparison of change-detection algorithms for monitoring eelgrass from remotely sensed data. Photogrammetric Engineering and Remote Sensing. 64(3): 207-216.

Muchoney, Douglass; Barry, M.; Haack, N. Change detection for monitoring forest defoliation. Photogrammetric Engineering and Remote Sensing. 60(10): 2099-2119.

Singh, A. Digital change detection techniques using remotely-sensed data. International Journal of Remote Sensing. 10(6): 989-1003.

Weismiller, R.A.; Kristof, S.J.; Scholz, D.K.; Anuta, P.E.; Momen, S.A. Change detection in coastal zone environments. Photogrametric Engineering and Remote Sensing. 43(12): 1533-1539.

Ground-Based Photo Monitoring

Frederick C. Hall

Abstract.—Ground-based photo monitoring is repeat photography using ground-based cameras to document change in vegetation or soil. Assume those installing the photo location will not be the ones re-photographing it. This requires a protocol that includes: (1) a map to locate the monitoring area, (2) another map diagramming the photographic layout, (3) type and make of film such as Kodak Elite-2®, ASA 200, (4) specific instructions for doing the photography, (5) instructions for when to re-photograph. Use a meter board to identify the topic of interest, to orient current and repeat photographs by focusing on the "1M" of the board, to ensure maximum depth of field by focusing on the "1M," and to provide a measured reference for grid analysis of change.

BASIC CONSIDERATIONS

Methods of photo monitoring have several things in common. Selection of a monitoring area must be based on the purpose of photographic sampling (similar to measurement sampling). The area must be located on one map and the sampling layout shown on a second map with directions and distances. When to photograph is usually determined by the activity being monitored. Camera locations and photo points must be permanently located with fence posts or steel stakes ensuring the same distance from camera to photo point. And, all pictures should be taken with a photo identification paper in view to permanently identify slides and negatives.

Area Selection

Selection of a monitoring area requires a great deal of professional expertise liberally mixed with artistic finesse. The **purpose** of photographic monitoring is the most critical factor to consider. It appears as two kinds of questions: where in the landscape is the topic of concern, and once on the area, what kind of change do I want to document? In some cases, "where" is straightforward. For example, documentation of logging impacts locates the area being logged (fig. 1), just as effects of beavers on a stream locate by the beaver activity. On the other hand, documentation of livestock grazing impacts requires understanding livestock distribution plus knowing the location of areas sensitive to grazing and the season of use that is most critical.

Once in an area, the real decisions must be made. Determine specifically what is to be documented for change (fig. 1). For example, the purpose of the photo monitoring was to document effects of a two-stage overstory removal and subsequent pre-commercial thinning on stand structure and ground vegetation. The camera location was selected within the sale area. Stand conditions of open pine and clumped reproduction across an opening were chosen for the photo point. The opening was selected to avoid tree crown encroachment between the camera location and photo point and to appraise logging effects on livestock forage. It was photographed before and after each entry.

When to Photograph

When to photograph is usually determined by the activity being monitored. Figure 1 illustrates a monitoring schedule dictated by logging activity. Photographs were planned for the first week in August to keep vegetation development consistent. They were taken just before logging and in each of the two seasons after cutting to document rapid changes in ground vegetation. Then, a 5-year re-photograph cycle was established to follow slower changes in both stand structure and ground vegetation. The routine was repeated with the second logging and a pre-commercial thinning.

If vegetation is a primary topic, consider establishing a fixed date for re-photography. An established date has two advantages. First, it offers an opportunity to evaluate yearly differences in plant phenological development. Second, it provides a consistent reference for comparing change over several years.

Maps to Locate the Monitoring System

After establishing the photo monitoring system, prepare maps to locate the area and to document the photographic layout. Assume the person installing the monitoring program will **not** be the one to find and re-photograph the area. Provide maps and instructions accordingly. Show on a local map the monitoring area locations.

Senior Plant Ecologist, USDA Forest Service, Pacific Northwest Region, Portland, OR, USA.

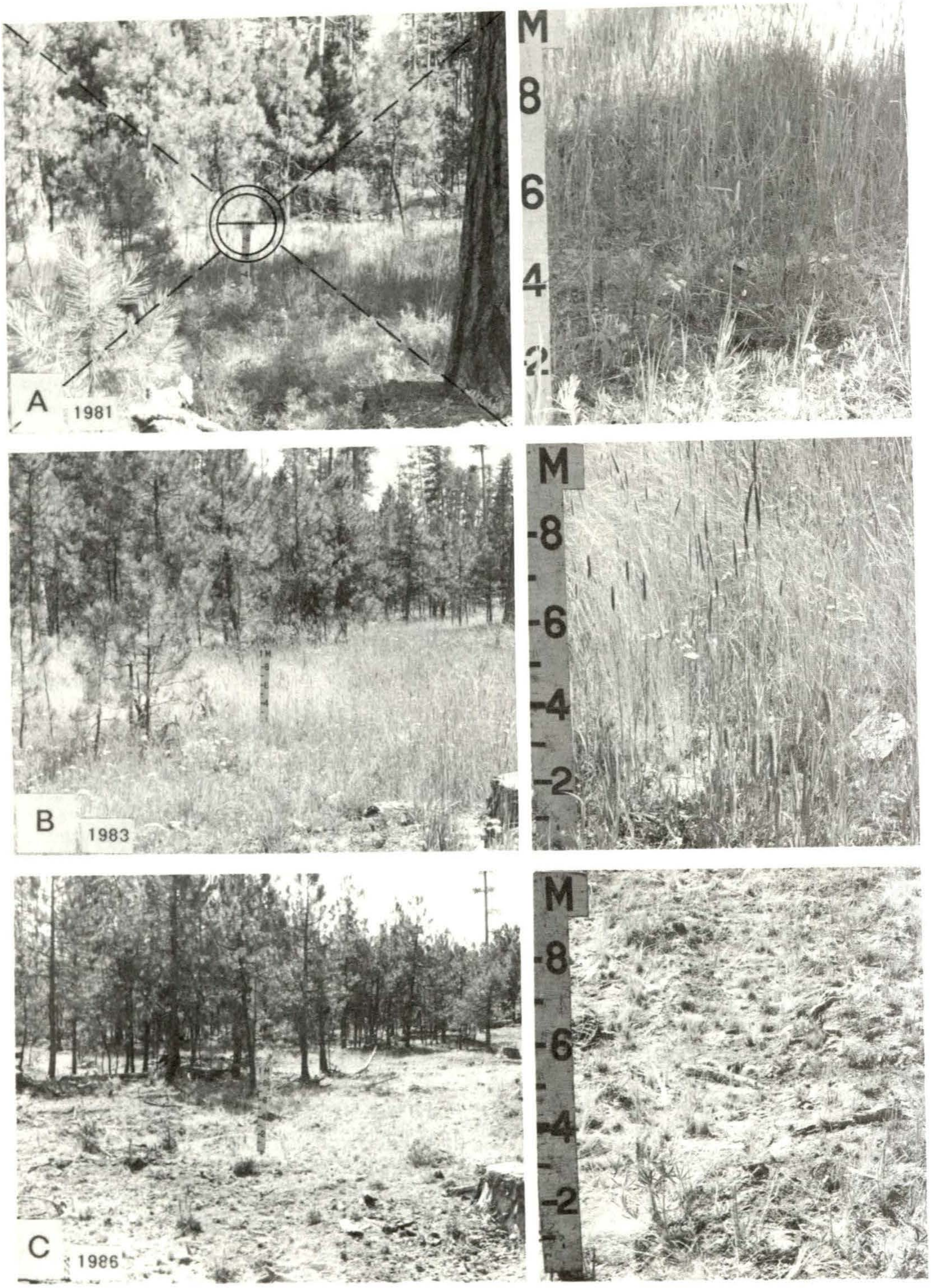


Figure 1.—*Photo monitoring change in a ponderosa pine/pinegrass community after two cutting entries. Two photos for each year are shown. Left is the general photo identifying the topic for monitoring and right is half of a close-up using the meter board as a reference. All photographs were taken the first week in August. (A) Before the first entry with native pinegrass. (B) The second growing season after the first partial overstory removal showing seeded domestic grass species. (C) The second growing season after the final overstory removal and before pre-commercial thinning. The opened stand and palatability of domestic grass species resulted in livestock grazing to a 3-in. stubble height. In (A), the camera focus ring is centered on the "1M" of the meter board to orient the photograph and ensure sharp focus at the topic.*

Select a witness post or tree to mark the area. Identify it with a permanent marker, such as an orange aluminum tag, and determine direction and distance to camera locations or transects. Inscribe these on the identification tag. Next, map the camera locations and photo points or transects with directions and distances. Note whether the direction is taken in magnetic or true degrees by indicating either "M" or "T." A 21-degree east declination in the Pacific Northwest must be accounted for.

Monitoring, by definition, means repeated observation. Therefore, all camera locations, transects, and photo points must be permanently marked. The recommended method is stamped metal fence posts. At 1998 prices, these cost about $2.25 each for a 5-foot size. Stamped metal has several advantages over strong "T bar" posts: they are flimsy and will bend if driven into by a vehicle or run over by an animal, they will bend flat and remain in the ground to mark the spot, they resist theft because they are just as difficult to pull out as a good fence post but are not worth the trouble, and they are easy to carry and pound.

Steel stakes often have been used and may be required on shallow soils. However, they have several disadvantages compared to flimsy fence posts: they will damage tires, hooves, or feet; they are often difficult to find; they are subject to theft; and if driven flush with the ground, they require a metal detector for location.

Same Distance Between Camera and Meter Board

One critical consideration in photo monitoring is the requirement for the **same distance** between the camera location and photo point for all subsequent photography on that sample. Any analysis of change depicted in the photographs can **only** be done when the distance remains the same. A standard distance for all photo monitoring is not required. Distance may vary from one camera location to another. Camera format may also change, such as first pictures with a 50-mm lens and next pictures with a 35-mm lens, but distance must remain the same.

Figure 2 illustrates the effect of changing distance on location and size of objects in the picture. The view is a test landscape where objects have been placed at various distances from the camera. A 50-mm camera lens on a 35-mm body was used at distances of 7 and 10 m from the meter board. Clear plastic was placed on each photograph and the objects outlined: solid lines for 10 m and dashed lines for 7 m. Then, the 7 m outline was reduced in size to exactly match the size of the meter board at 10 m and the two outlines overlaid (C in fig. 2). Clearly, the size and location of objects are different. The reason is change in geometrical relationships between the camera and meter board. Angles from 7 m are different from those at 10 m.

Changing camera focal length, from 50 to 35 mm, will still produce very similar pictures. At 7 m, the 50-mm lens is shown in figure 2(A) while a 35-mm lens at the same distance would produce a photograph similar to figure 2(B). However, if both focal lengths are taken from the same distance and outlines adjusted in size to the meter board, both location and size of objects are will be the same. They are the same because the geometrical angles between camera and meter board are the same. A 35-mm lens simply has a wider view of the landscape.

Photograph Identification

Each photograph should be identified by site name, photograph number, and date. The critical factor is identification of **negatives** for color or for black and white pictures. Slides can be written on. However, there is no room to identify negatives. Placing a photo identification card in each picture view ensures a permanent record on the negative. This has been one my biggest problems—negative identification. The only identification for negatives of figure 1 is their envelope!

Paper color is the next consideration. Plain white or light colors, common in the office environment, are not suitable because they are too light in color and will burn out when photographed. The recommended paper color is either Hammermill Brite Hue Blue® or Georgia Pacific Papers Hots Blue®. Tests have shown these darker blue hues are superior to other darker colors such as green and yellow.

Cameras and Film

A wide variety of cameras and film are available and suitable for use. For example, a 27-exposure disposable camera using 35-mm color film with a 35-mm focal length lens is available for about $15. It is compact enough to fit in a shirt pocket. Processing for two 4- by 6-inch prints is about $14 for a total of $29. The other end of cost might be a fine zoom lens for $800 on a sophisticated 35-mm camera body costing $800 capable of 36 exposures using any 35-mm film. Purpose and longevity of the photo monitoring program are major factors in camera and film selection.

Cameras

Over the past 40 years, I used a pair of good quality 35-mm reflex cameras and 50-mm lenses (about $800 each at 1998 prices). One had color and the other had black and white film. Today, I use a nice quality weatherproof 35-mm camera with 35-mm lens, flash, and date-back, capable of 36 exposures, and compact enough to fit in a shirt pocket.

Several things might be considered in selecting cameras. (1) Is photo monitoring the primary purpose of the

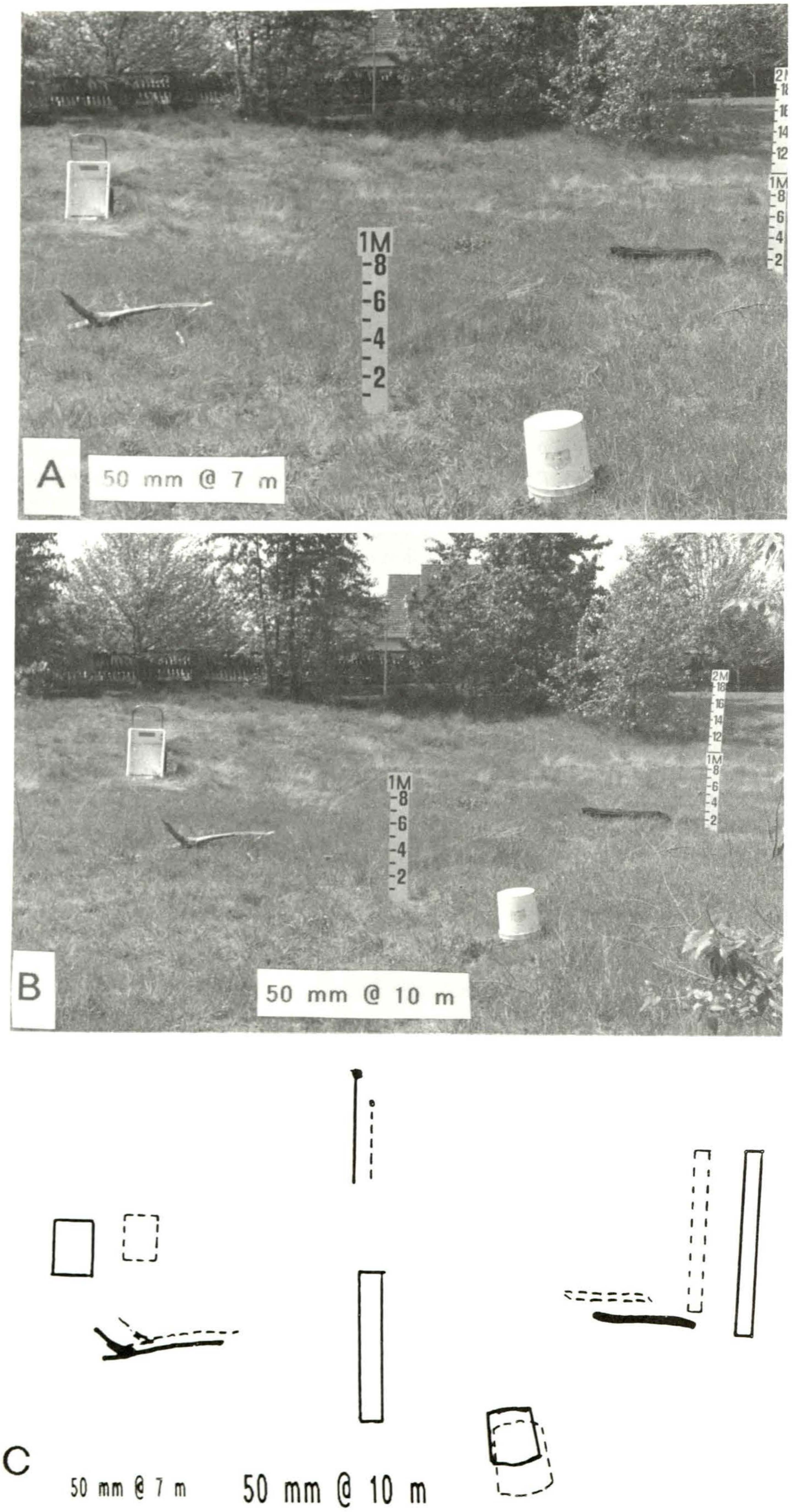


Figure 2.—*Photographic test landscape used to evaluate camera to photo point distance and camera focal length. (A) A photo taken with a 50-mm lens on a 35-mm camera body 7 m from the meter board. (B) The same camera 10 m from the meter board. Objects in each photo were outlined on a clear plastic overlay: solid lines for 10 m and dashed lines for 7 m. Then the plastic outline for 7 m was reduced to exactly match the size of the meter board at 10 m. Finally, in (C), both outlines were overlaid to show difference in both object size and location. Differences are caused by change in geometric angles between the camera and meter board as distance changes.*

camera? If it is, then a pocket-size 35-mm focal length is most convenient. Seriously consider a disposable camera for about $15. (2) Do you contemplate other uses? Will a simple, wide angle lens camera suffice? Is a flash necessary for poor light conditions or indoor use? Then, a simple wide angle camera in the $150 bracket might be a choice. (3) Do you want a variety of focal lengths? Zoom lens cameras come in many forms and prices. Some under $200 are available, but their lenses require nearly full sunlight or flash, which tends to limit their usefulness for photo monitoring, particularly in low-light forested conditions. Good quality zoom or interchangeable lens cameras start at about $500.

Film

Three choices are available in film: (1) color slides, (2) color prints, or (3) black and white. I have always used color slide film in one camera and black and white in the other. Color slides are used for oral presentations and black and white for publishing. Both cameras are connected to an aluminum strap 1 inch wide and bent into a "U" so both can be handled with one hand.

I use both color and black and white because color film, slide or print, will fade with time and black and white will not. Once an exposure has been made on slide film, little can be done to enhance the image. Negative films, for either color or black and white, offer an opportunity to modify images when making prints. Different print paper may be used, time of exposure can be adjusted, and overexposed or underexposed parts may be "dodged" to enhance the image.

All film comes in various degrees of graininess. This is usually identified by the film speed; the higher the speed, the grainier the film. For example, ASA 64 is a very fine grain film whereas ASA 800 is quite grainy. ASA 800 color film is used in disposable cameras without flash.

Color film varies in color tones between brands from a single manufacturer, such as Kodak's Kodachrome® compared to Ektachrome Elite®, and between manufacturers such as Fuji and Kodak. Film developing may produce different tones from the same kind of film. Color prints can vary from the same negative depending upon how the prints were made. Time of exposure and kind of paper are critical. Do not cheapen your photography by cut-rate processing.

PHOTOGRAPHIC TECHNIQUE

Photographs identify a specific topic of interest (fig. 1). A meter board, or other size, control board, is placed at the topic for several reasons: It (1) identifies the item to be monitored, (2) establishes a camera orientation reference point for subsequent photography, (3) ensures greatest depth of field at the topic by focusing the camera on the "1M" of the board, and (4) establishes a constant-size reference by which change may be documented—with grid analysis, for example.

Photo Sampling Guidelines

Several steps might be considered when establishing photo monitoring. Figure 1 will be used as an example.

Define the topics of interest. The topics in figure 1 are effects of converting old-growth ponderosa pine/pinegrass, *Pinus ponderosa* P.&C. Lawson/*Calamagrostis rubescens* Buckl., to a young forest, response of residual understory to thinning, and reaction of ground vegetation to overstory manipulation.

Next, define what coverage is desired in the monitoring area. How many camera locations and photo points are desired? What pre-cutting stand conditions are important?

In many cases, details might be desired that are not accommodated by a meter board 7 to 10 m distant. Close photos, one on each side of the meter board, are recommended. These are taken at 1.5 to 2 m distance and show details on-the-ground in approximately a 1.5- by 1.5-m area. The concept is a general photo and two close-up photos to document change (fig. 1).

Consider the advantages of multiple photo points from the same camera location or multiple camera locations focusing on the same photo point. Advantages are twofold. First, relocation tends to be easier because only one point must be located that will serve two or more views. Second, one point showing several views tends to tie the monitoring area together.

Distance From Camera to Photo Point

Exact replication of distance for all re-photos is the reason camera locations and photo points must be permanently marked in the field. My preferred system is with flimsy fence posts. However, establishment of a fixed distance for all photo monitoring is not required. Tailor the camera-photo point distance to the topic being monitored.

Topic Description

Describe the setting and topic to be photographed each time photos are taken. Figure 1 illustrates a general photo and one of two close-up pictures of ground conditions. Record activities within the general photo and plant species, bare ground, or other items and their estimated cover for the close-up pictures.

Camera Orientation and Focus

Consistent re-photography requires a reference point to orient subsequent views. A meter board serves this purpose. The objective is to have the meter board remain constant while items within the view change. Figure 1 illustrates three repeat photographs of a ponderosa pine/pinegrass community that was cut twice. Figure 1(A) illustrates how the camera focus ring is placed over the "1M." This accomplishes three things: (1) It provides a common orientation point for the first and subsequent photographs. (2) It provides a locus for focusing the camera for maximum depth of field. When the meter board is placed at the topic of interest, the topic should always be in sharp focus. And (3), it serves as a measurement reference for grid analysis of change.

Close-up pictures on either side of the meter board help monitor the topic under study. After taking the general photo, walk up to the meter board and photograph it on each side. With a 50-mm lens, stand 2 m (7 feet) away, or with a 35-mm lens, stand 1.5 m (5 feet) away. Figure 1 illustrates partial close-up photos using a 50-mm lens. The critical factor is to always place the top of the meter board all the way up in a corner of the view. When you stand 2 m away with a 50-mm lens, the bottom of the board will be at the bottom of the picture as shown.

GRID ANALYSIS

The meter board is also used as a size reference for analyzing changes. One system is grid analysis, illustrated in figure 3. A pair of photographs, preferably in color and enlarged to 6 by 9 inches, is selected on which to document change in some topic. In figure 3, the topic is riparian shrub profile area from 1981 to 1996.

A clear plastic grid is adjusted in size to exactly match the meter board measurements as follows. The meter board is measured on the photograph, such as 24 mm, and divided by the measurement on a grid master such as 30 mm for a reduction in size of the master to 80 percent. The reduced grid master is then printed on a clear plastic overhead transparency sheet and taped at one edge to the photograph. One-edge taping permits lifting the clear grid to closely inspect the photograph.

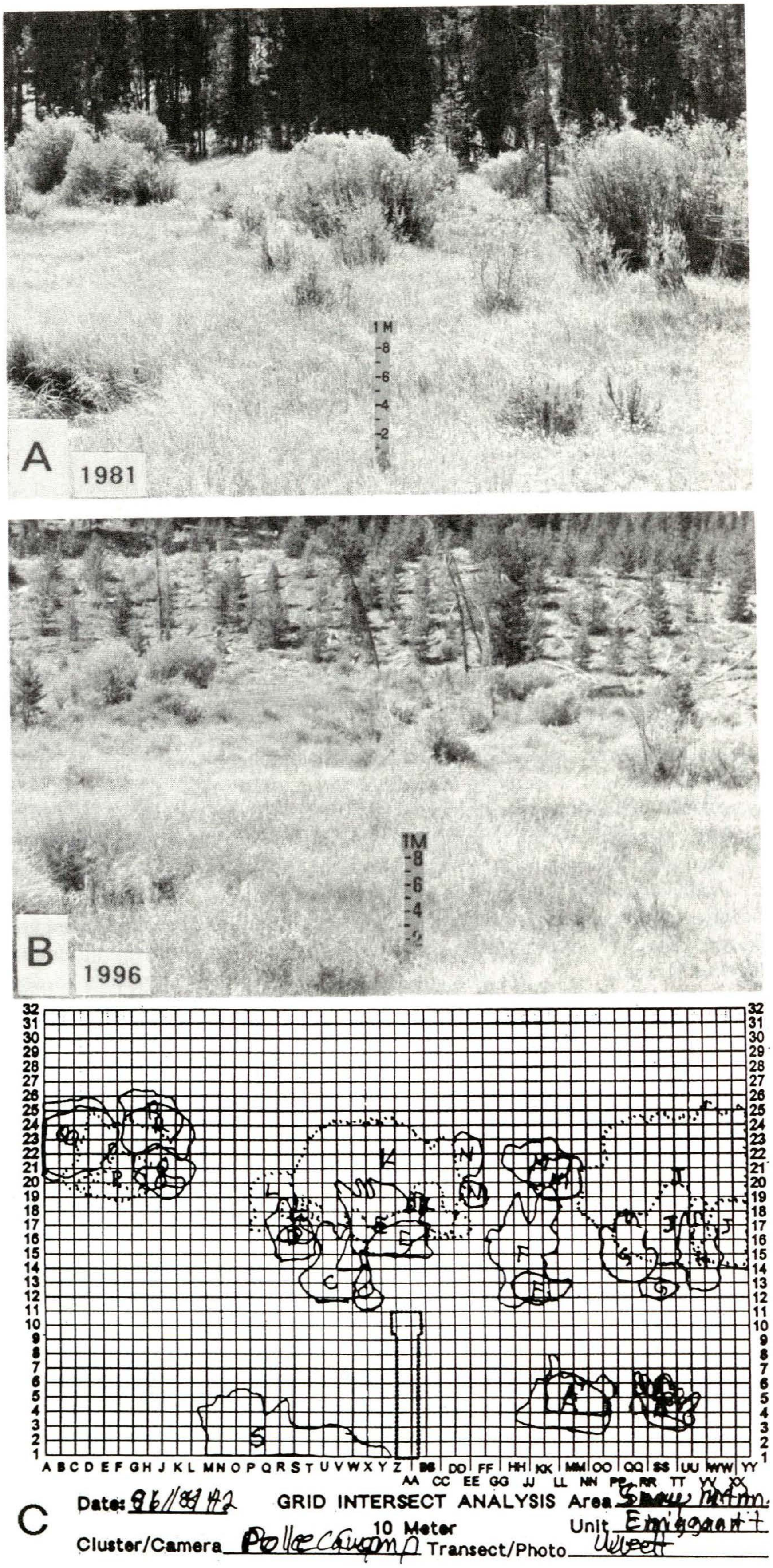
Next, topics of interest are outlined on the grid. When outlining, be careful to place the line precisely on the edge of the topic. Exact placement is required because an intersect under the line is counted. Intersects within each outline are counted and recorded for each photograph. Finally, the number of intersects are compared between photographs to estimate change. In figure 3, shrub profile intersects were 396 for 1981 and only 222 for 1996. Unpublished test results using seven observers indicate this is significant at $P = 0.01$. The outlines may also be compared as shown in figure 3(C).

SUMMARY

Ground-based photo monitoring is a rapid system for monitoring changes in ground conditions such as vegetation and soil. For best results, map the location so others can find and re-photograph, permanently mark each camera location and photo point so distance between the two does not change, and use a meter board or equivalent to mark the topic of concern, to orient later photographs, ensure sharp focus on the topic, and adjust analysis grids.

ACKNOWLEDGMENTS

The following people reviewed this manuscript: Virginia Hokkanen, editor; Deborah Konnoff, Aquatic Resources Coordinator; and David Bridgwater, Remote Sensing, all three from the USDA Forest Service, Pacific Northwest Region, Natural Resources Unit, Portland, OR, USA.


1M
-8
-6
-4
-2
A
1981
1M
-8
-6
-4
-2
B
1996
32 31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1
A B C D E F G H J K L M N O P Q R S T U V W X Y Z BB DD FF HH KK MM OO QQ SS UU WW YY
AA CC EE GG JJ LL NN PP RR TT VV XX
C

Date: 96/1/88 #2 GRID INTERSECT ANALYSIS Area Snow Mtn.

10 Meter Unit Emigrant

Cluster/Camera Pole Camp Transect/Photo West

Figure 3.—*Grid analysis of change in riparian shrub profile from 1981 to 1996. A master grid was reduced on a copy machine so the meter board profile on the grid exactly matched the meter board in the photo. This reduced grid was then copied onto clear transparency plastic and taped to the photograph. Each shrub under the grid was outlined. The two grids were then overlaid for comparison as shown in (C). These grids are permanent documentation of changes on the photographs so they must be labeled with the study and site identification.*

Development of A Highly Automated System for the Remote Evaluation of Individual Tree Parameters

Richard Pollock

Abstract.—A highly-automated procedure for remotely estimating individual tree location, crown diameter, species class, and height has been developed. This procedure will involve the use of a multimodal airborne sensing system that consists of a digital frame camera, a scanning laser rangefinder, and a position and orientation measurement system. Data from the multimodal sensing system will be processed by a model-based procedure for the recognition of individual tree crowns in aerial images. Both the multimodal sensing and tree crown recognition components have been separately tested, and data to test their integration have recently been acquired as part of an in-progress experiment. The tree crown recognition procedure has been extended to use data from the scanning laser rangefinder to increase the reliability of individual tree crown isolation and to estimate tree height. Depending on the results of the experiment, the integrated system may be useful in many forest inventory activities, delivering data at a low cost relative to its value.

The overall objective of this work is to develop a highly automated procedure for remotely estimating the location, vertically projected crown diameter, species class, and height of large numbers of individual trees from digital image and range data acquired from an aircraft. The procedure is being developed as the integration of a multimodal airborne sensing system that consists of a digital frame camera, a scanning laser rangefinder, and a position and orientation measurement system (POMS), with a model-based procedure for the recognition of individual tree crowns in aerial images. Both the multimodal sensing system and the tree crown recognition procedure have been separately tested. Data (including reference data) have recently been acquired for testing the integrated system.

MULTIMODAL SENSING SYSTEM

The multimodal sensing system is designed to simultaneously acquire vertical aerial images and dense spot elevation data in a manner that allows the spatial relationship between the spot elevations (or the cells in a regular-grid digital elevation model created from the spot elevations) and image locations to be readily determined. This facilitates the determination of the height of objects portrayed in the images, and the differential rectification (removal of scale variations due to scene elevation variation and camera tilt) of the images.

The currently implemented system incorporates an Optech Airborne Laser Terrain Mapper (ALTM) 1020 scanning laser rangefinder system, a Kodak DCS420 natural color digital frame camera[1], and a POMS consisting of a global positioning system (GPS) receiver and an inertial measurement unit (IMU). The camera and rangefinder sensing head are attached to a rigid mount (fig. 1) so that their central optical axes are parallel, and the scanning plane of the rangefinder is parallel to the rows of the camera detector array.

A Kodak DCS420 camera incorporating a 28-mm lens can acquire sharp aerial images with an approximately 20-cm ground projected pixel dimension and an approximately 310- by 207-m ground footprint at a 85- to 90-mph ground speed and at 620 m above ground level under most daylight illumination conditions. This camera configuration has a 28-degree long-axis field of view, which is close to the ALTM 1020 30-degree maximum field of view. The ALTM 1020 can be programmed to acquire spot elevations with an approximately 1-m horizontal ground spacing under these flying conditions (daylight illumination has no effect on ALTM 1020 performance). The Kodak DCS420 camera can be programmed to operate with a fixed shutter speed and automatic aperture adjustment (the settings used to capture an image are stored in the image file that is downloaded from the camera). This produces sets of images with close-to-uniform overall tone even when scene illumination varies during a flight.

Software controls and records images from the camera during the flight, and calculates from the POMS data the position and orientation of the camera at the instant of exposure of each image frame. This software was built at

---

Research Scientist, Advanced Systems Applications, Alberta Research Council, 3rd Floor, 6815 8th Street NE, Calgary, Alberta, Canada, T2H-7H7. Voice: (403) 297-7558, fax: (403) 297-2339, e-mail: pollock@arc.ab.ca.

[1] *The mention of a specific commercial product in this article is solely for the reader's information and is not intended to be an endorsement of the manufacturer's product.*

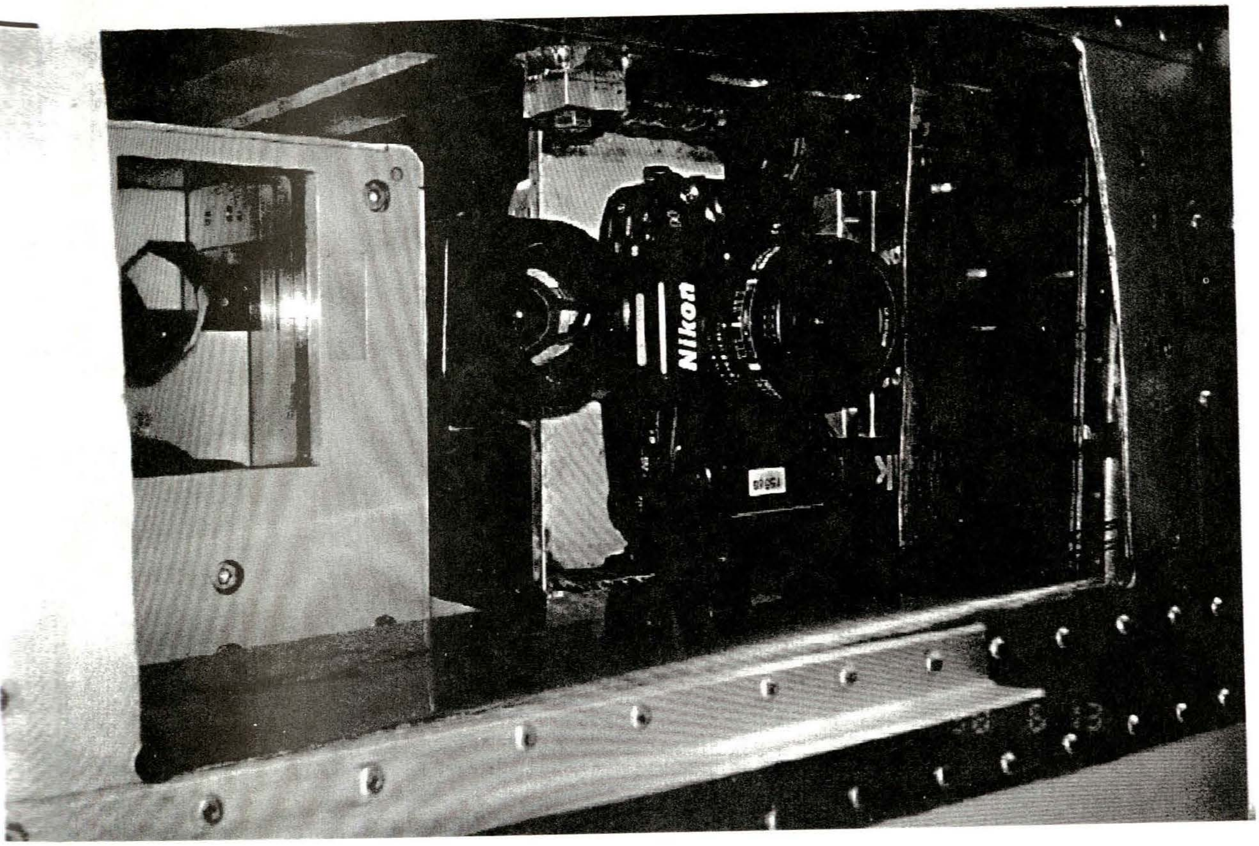


Figure 1.—*View of the scanning laser rangefinder sensing port (left), a video camera for in-flight navigation (middle), and the digital frame camera (right) as seen through the observation opening in the floor of the aircraft.*

the Alberta Research Council (ARC) under contract to New-Tech Remote Sensing of Calgary, Alberta. Further ARC software creates a regular-grid DEM from a set of spot elevations acquired with the rangefinder, differentially rectifies each image frame using the DEM and the frame-specific position and orientation data, and composes the rectified image frames that intersect a user-specified geographic region into a single mosaic image (fig. 2). The differential rectification procedure involves an initial manual step to check for significant misalignment of the camera and rangefinder optical systems using a sample of the image and elevation data, and to evaluate a global correction. Beyond this step, the rectification procedure is completely automatic. After the user specifies the mosaic region, all of the mosaic composition steps are automatic, including the placement of the joints between component images and the global tonal balancing.

Although care is taken in establishing the sensor alignment, it may not be perfect because it is done after the instruments are installed in the aircraft. Also, aircraft vibration and repetitive landing shock may cause significant misalignment. A new sensor mount with improved vibration and shock resistance, and a pre-installation sensor alignment procedure are currently under development.

TREE CROWN RECOGNITION PROCEDURE

The original tree crown recognition procedure is designed to recognize tree crowns in monocular high spatial-resolution aerial images of scenes containing boreal or cool temperate forests in a leafed state, and is based on a model of the image formation process at the scale of an individual tree. This model provides a means of applying specific scene and image formation knowledge to the recognition task. Natural variation of tree crown size, shape, and composition is considered, as well as the tree-image variation (including the effect of height displacement) that is a function of image geometry. The procedure also involves user-generated training data and exploits a basic constraint on the spatial relationship of neighboring trees.

The procedure associates instances of a three-dimensional shape description with locations in a scene image so that the descriptions estimate the visible scene extent of tree crowns that existed at the corresponding scene locations when the image was acquired (fig. 3). This provides an

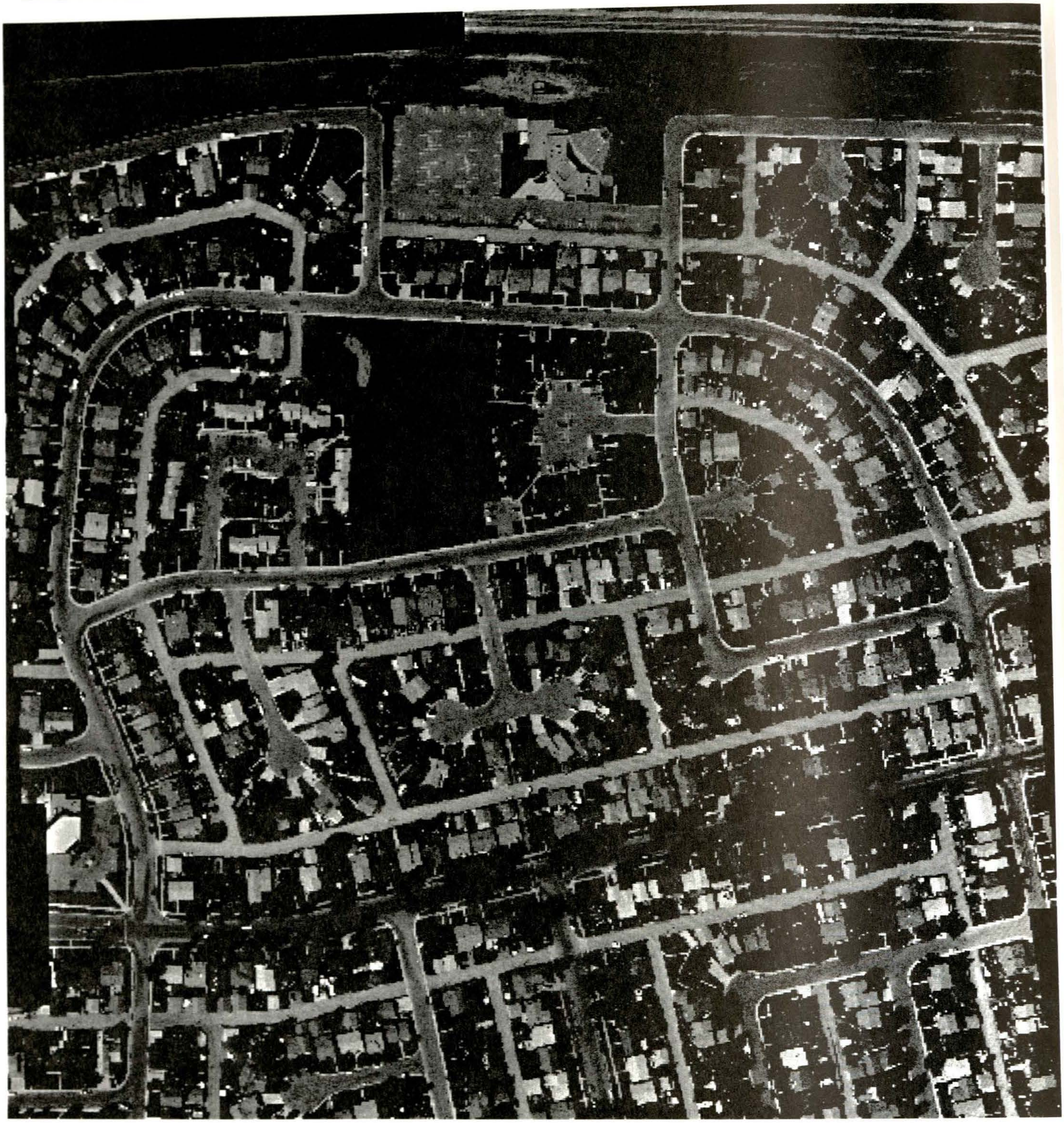


Figure 2.—*A portion of a differentially rectified image mosaic that was automatically generated from data acquired with the multimodal sensing system. This portion includes all or part of eight separate image frames. The original image is natural color and has 20-cm pixels. The image has been highly subsampled for printing and display here.*

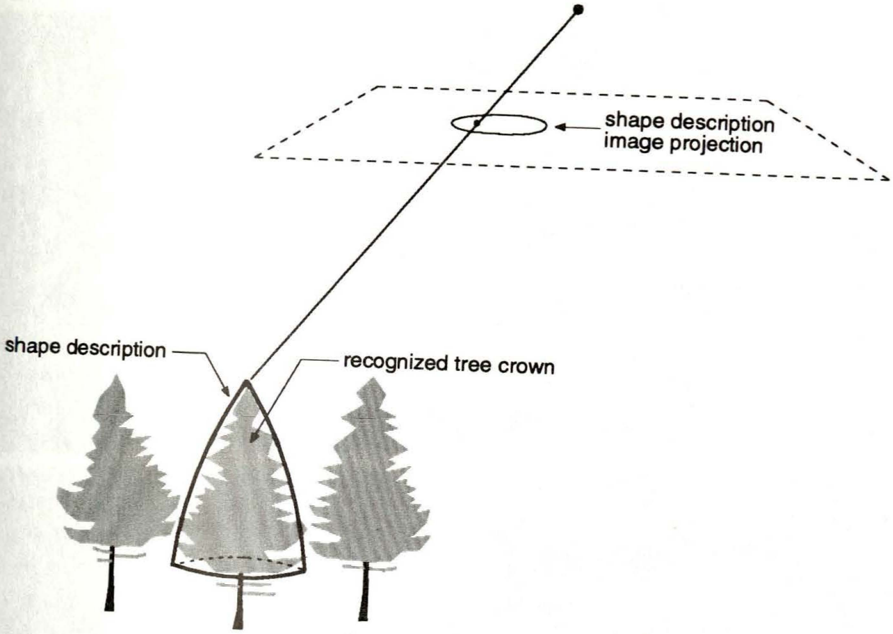


Figure 3.—*The tree crown recognition scenario.*

estimate of the tree location and the average horizontal diameter of the vertical tree crown projection. The projection of a shape description onto the image is an estimate of the image extent of a single tree crown. Species classification is based on the multispectral image values within these image extents (i.e., classification is done on a whole crown-image basis rather than on a pixel-by-pixel basis). Further details on the original procedure may be found in Pollock (1996).

Two tests of the original procedure have been conducted. The first test was conducted on images of scenes within the research forest of the former Petawawa National Forestry Institute (PNFI) near Chalk River, Ontario, Canada. The second test was conducted on images of scenes within the Athabasca 24 compartment of the Weldwood of Canada, Ltd., forest management area near Hinton, Alberta, Canada.

PNFI Test

The PNFI images were acquired during the morning of August 16, 1988. The scenes contain mixed forest and represent many stand types, including mixed hardwood and softwood stands, and a wide range of individual tree sizes. The images were acquired in multiple wavelength regions with the second generation of the Multi-detector Electro-optical Imaging Scanner (MEIS II), an airborne pushbroom scanner (McColl *et al.* 1983). The images have a 36-cm ground-projected pixel dimension. Some of the scene variation and samples of the results that were produced by the recognition procedure are shown in figure 4.

PNFI personnel evaluated various attributes (including crown diameter) of a sample of 587 overstory trees that were distributed among twenty-four 20- by 20-m square sample plots in the scene, and manually estimated the crown apex location for 548 of the sample trees. These reference data were used to assess the accuracy of the recognition procedure.

The errors in the automatic recognition results for the PNFI test were mostly omission errors. These errors were evidently caused by non-ideal crown irradiation, irregular crown form (especially for some hardwood trees), partial occlusion of tree crowns due to height displacement, and faulty interpretations of tight clusters of tree crowns as relatively large tree crowns. The errors in automatic and manual image-based crown diameter estimates were comparable. Both sets of estimates tended to be low relative to the ground measurements, probably because of tree crown intersection and the failure to resolve branches at the outer crown extent that are visible from the ground. Detailed descriptions of the test results are given in Pollock (1996).

Athabasca 24 Test

The Athabasca 24 images were acquired during the early- to mid-afternoon on July 24, 1996. The scenes contain mostly coniferous forest and some aspen stands, and have a less varied species composition than the PNFI scenes; nevertheless, the Athabasca 24 scenes represent a wide range of tree sizes and crown shapes. The images were acquired in multiple wavelength regions with the Compact Airborne Spectrographic Imager (CASI) (Babey and

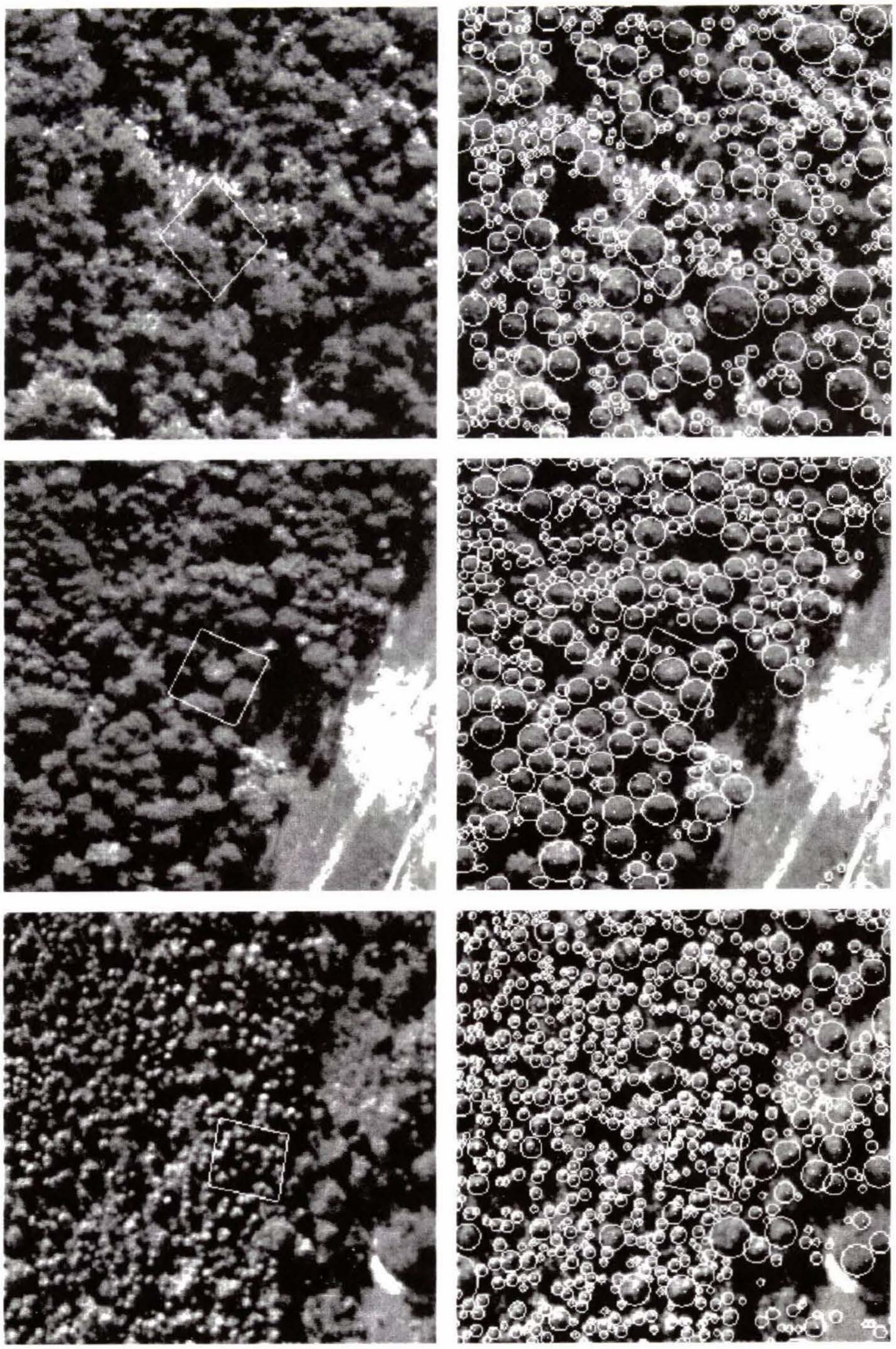


Figure 4.—*Subimages from the image data and automatic individual tree crown recognition results for 1-ha PNFI subscenes. The subimages were extracted from the visible green wavelength channel of the test image data. The image projection of the shape description boundary for each of the recognized crowns is superimposed in white on the subimages in the right column. The boundary of a 20- by 20-m ground sample plot is superimposed in white on all subimages.*

Anger 1989). The images were acquired with a 60-cm ground-projected instantaneous field of view, and resampled to a 50-cm pixel dimension during rectification. Some of the scene variation and samples of the results that were produced by the recognition procedure are shown in figure 5. The results show that the recognition procedure is largely able to accommodate the variation represented by the scene.

Early in the examination of the Athabasca 24 image data and the recognition results, we concluded that the spatial resolution of the image data and the amount of aliasing present were very likely significant obstacles to both manual and automatic tree crown recognition. Field visits confirmed that many relatively small trees of merchantable size could not be manually resolved in the image data. Because of this, only a superficial assessment of the results (relative to the PNFI test) was conducted. Funds that were to be spent on more intensive fieldwork in Athabasca 24 have been diverted to the assessment of the results from the test of the current integrated system.

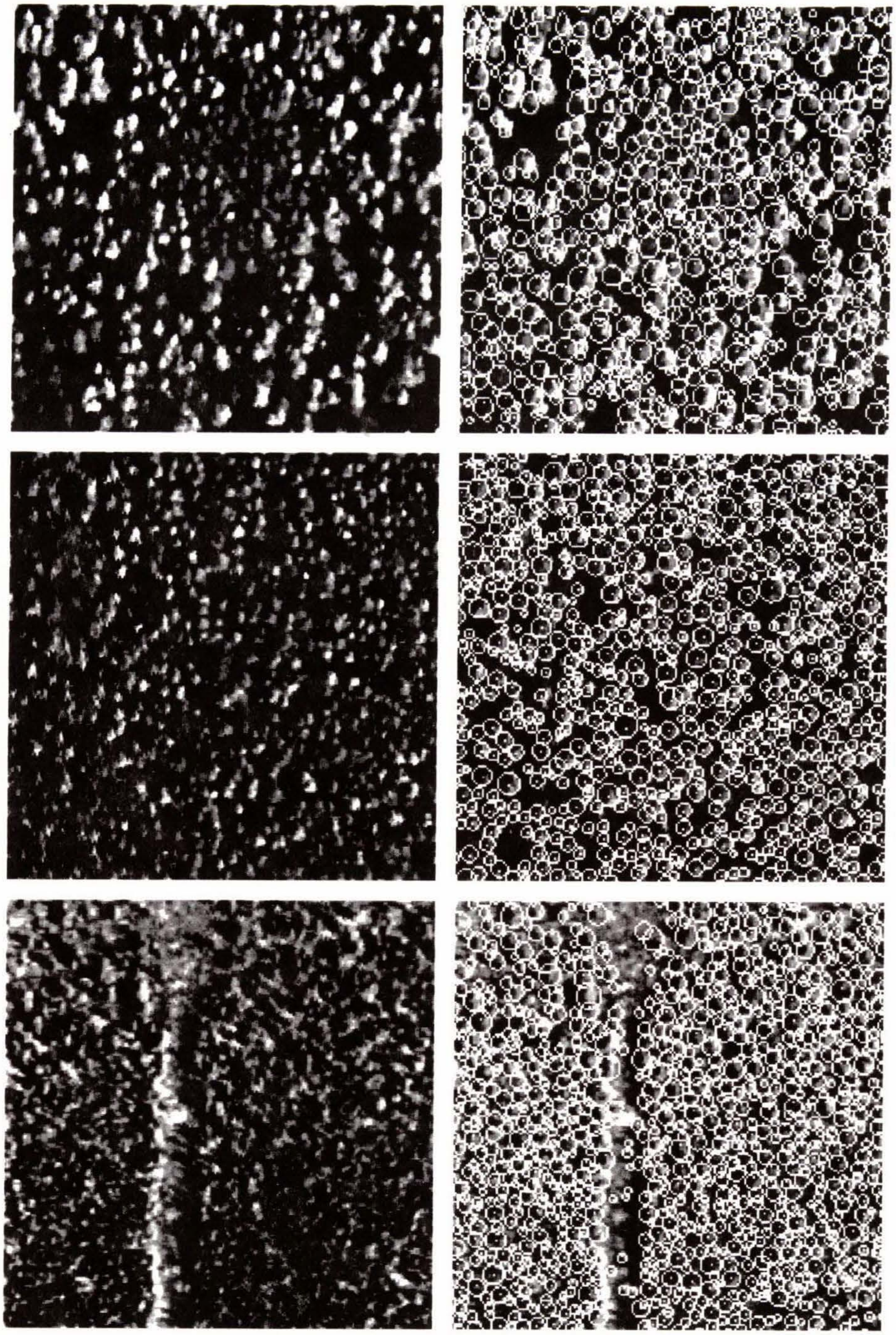


Figure 5.—*Subimages from the image data and automatic tree crown recognition results for 1-ha Athabasca 24 subscenes. The subimages were extracted from the visible green wavelength channel of the image data. The image projection of the shape description boundary for each of the recognized crowns is superimposed in white on the subimages in the right column.*

A comparison of the recognition results within six 1-ha scene regions with on-foot field observations revealed the following common errors: (1) trees with a crown diameter of less that 1 m were often missed, even when they grew in uncrowded conditions; (2) tight groups of small trees were often automatically recognized as a single tree; (3) where crowns were relatively close together, shorter and smaller crowns were often missed; (4) forked trees were usually recognized as single crowns; and (5) members of tight groups of aspen have highly irregular crowns and were often either missed altogether (i.e., interpreted as ground vegetation) or were interpreted as a group of relatively few trees. These errors usually could not be recognized through manual interpretation of the image data alone.

The field observations revealed that near-infrared/red/green false-color composites of the Athabasca 24 data contain color-distinctions between different coniferous species (lodgepole pine, white spruce, tamarack) and very obvious color distinctions between coniferous species and aspen, at least where individual tree crowns are easily recognized. An automatic supervised classification of tree crown image regions based on multispectral image values within the direct irradiation portions of these regions yielded results that were consistent with manual interpretation results.

Summary

The PNFI and Athabasca 24 tests of the original recognition procedure strongly suggest that improved spatial resolution is required for the procedure to produce tree recognition results that would be generally accepted for use in forestry. The tests also indicate that greater accommodation of the effects of crowding on tree crown images (irregular crown form and lighting) is required. Color-infrared image data provide a basis for a useful species classification. The procedure does not address the estimation of tree height, which is a significant omission because tree height is highly valuable for the estimation of timber volume.

INTEGRATION

Kodak DCS420 three-color aerial images with a 20-cm ground-projected pixel dimension allow better manual resolution of small trees than do the MEIS II and CASI images involved in experiments described earlier (both of these data sets were acquired at the finest spatial-resolution possible at the time with a standard twin-engine aircraft platform). This is significant with respect to the findings of the Athabasca 24 experiment described above. Also, the Kodak DCS cameras are available in green-red-nir (color infrared) versions, which is significant with respect to tree species classification.

The ALTM 1020 can be programmed to determine range according to either the first or the last pulse in the return pulse-train associated with an outgoing laser pulse (commonly referred to as operating in, respectively, "first pulse" or "last pulse" mode). In principle, the ALTM 1020 produces spot elevations for the top surface of a forest canopy when operating in first-pulse mode, and produces spot elevations for beneath-canopy terrain when operating in last pulse mode. In fact, a significant return pulse may only be returned once the outgoing pulse has penetrated some distance into a forest canopy, and a trailing pulse may be returned by a tree trunk or dense undergrowth rather than what may be considered to be the ground). Data from the ALTM 1020 have a clear-terrain elevation precision of 15 cm, so it is reasonable to expect that such data could be used to estimate tree height to a precision within 1 m.

Although the ALTM 1020 cannot collect first- and last-pulse data simultaneously, which necessitates dual flight passes for estimating tree height, newer models of the ALTM have this capability.

We have shown that the spatial registration of spot elevations and image data from the multimodal sensing system is at a submeter accuracy. Therefore, we expect that tree crown recognition results could be used to automatically select first-pulse spot elevations that coincide most closely with the tops of tree crowns (as opposed to the margin of the crowns or to between-crown gaps), and last-pulse spot elevations from pulses that have traveled between tree crowns on their way to the ground. Software that performs this type of spot-elevation selection has been built at ARC. In addition, the tree crown recognition software has been extended so that it will use local elevation minima in a top-of-canopy elevation model as an additional cue for separating crowded tree crowns that may have irregular form and lighting.

IN-PROGRESS EXPERIMENT

The in-progress experiment is designed to answer the following questions:

1. How accurate is the georeferencing of the data from the multimodal sensing system?
2. How well does the ALTM 1020 determine ground elevation through different types of forest canopy?
3. How accurately can tree height be estimated with the integrated system?
4. Can top-of-canopy elevations be used to improve the separation of crowded tree crowns?

Data were acquired with the multimodal sensing system on July 25, 1998 for a 5- by 10-km site near Manning, AB, Canada. This site contains a variety of boreal forest stands. Markers that are visible in the aerial images have been placed over 26 points distributed throughout the site whose locations have been determined to 3 cm accuracy with GPS; these data will be used to answer the first question. Dense networks of ground elevations have been measured within a variety of tree stands (e.g., black spruce, white spruce, aspen) using a total station instrument; these data will be used to answer the second question. Large-scale (1:800) 70 mm format photographs have been obtained for 50 plots within the site (tree height can be manually estimated with a 10 cm accuracy on the basis of these photographs); these data in combination with ground visits will be used to answer the third and fourth questions.

CONCLUSION

A highly automated system for the remote evaluation of large numbers of individual tree crowns has been built by integrating a multimodal sensing system with a tree crown recognition procedure, both of which have already been tested. Data have recently been acquired with the multimodal sensing system for a site in northern Alberta. These data, together with large-scale airphotos and ground reference data that have also been collected, will be used to assess the performance of the integrated system. Depending on the results of the in-progress experiment, the integrated system may be useful in many forest inventory activities, delivering data at a low cost relative to its value. This work has also set the stage for exploiting improvements in scanning laser rangefinder, digital camera, and POMS technology. In fact, the equipment that the existing multimodal sensing system is built from is no longer state of the art; now commercially available are digital frame cameras with larger detector arrays and faster data downloading components and scanning laser rangefinders with a greater sampling rate and simultaneous first- and last-pulse recording capability.

ACKNOWLEDGMENTS

Initial financial support for the tree crown recognition work was provided by the Natural Sciences and Engineering Research Council of Canada in the form of a Postgraduate Research Fellowship and an Industrial Postdoctoral Research Fellowship to the author, and research grants to Robert J. Woodham, Professor and Head, Department of Computer Science, University of British Columbia, and by the Institute for Robotics and Intelligent Systems (one of the Canadian Networks of Centers of Excellence). Don Leckie, Research Scientist in the Landscape Management Network at the Pacific Forestry Centre of Natural Resources Canada, provided access to the MIES II image data and associated reference data used in this work. Current financial support for the multimodal sensing and system integration work is provided by the Alberta Research Council and New-Tech Remote Sensing of Calgary, AB, Canada.

The following people reviewed this manuscript: Jan Mulder, Alberta Research Council, Calgary, AB, Canada, and David Stonehouse, New-Tech Remote Sensing, Calgary, AB, Canada.

LITERATURE CITED

Babey, S.K.; Anger, C.D. 1989. A compact airborne spectrographic imager (CASI). In: Proceedings of IGARSS '89—Quantitative remote sensing: and economic tool for the nineties; 1989 July; Vancouver, BC: 1028-1031.

McColl, W.D.; Neville, R.A.; Till, S.M. 1983. Multidetector electro-optical imaging scanner MEIS II. In: Proceedings of the 8th Canadian symposium on remote sensing; 1983 May: 71-77.

Pollock, Richard. 1996. The automatic recognition of individual trees in aerial images of forests based on a synthetic tree crown image model. Vancouver, BC: University of British Columbia. 220 p. Ph.D. dissertation.

Using Landsat Thematic Mapper and SPOT Satellite Imagery to Inventory Wetland Plants of the Coeur d'Alene Floodplain

F.M. Roberts and P.E. Gessler

Abstract.—Landsat Thematic Mapper (TM) and SPOT Satellite Imagery were used to map wetland plant species in the Coeur d'Alene floodplain in northern Idaho. This paper discusses the methodology used to create a wetland plant species map for the floodplain. Species mapped included common cattail (*Typha latifolia*); water horse-tail (*Equisetum fluviatile*); water potato/arrowhead (*Sagittaria* spp.); and wild rice (*Zizania aquatica*). Useful classifications were derived and lessons were learned about the timing of image acquisition and field data collection. This will guide improved classifications in the future.

Remote sensing technology and GIS are powerful tools useful in analyzing complex ecosystem problems. The objective of this research work was to use these tools to map and quantify a part of the wetland plant components of the Coeur d'Alene floodplain ecosystem, specifically common cattail (*Typha latifolia*), water horsetail (*Equisetum fluviatile*), water potato/arrowhead (*Sagittaria* spp.), and wild rice (*Zizania aquatica*). These four plant species have been identified by the U.S. Fish and Wildlife Service (FWS) as waterfowl food items in the ecosystem. The Coeur d'Alene River floodplain was the area chosen for the research (fig. 1).

During the past 100 years, much of the Coeur d'Alene River floodplain became contaminated with heavy metals such as zinc, lead, and cadmium from mining activities. Since the 1880's, mining and smelting activities in the Kellogg, Smelterville, Wallace, and adjacent areas have released an estimated 75 million tons of tailings into the South Fork of the Coeur d'Alene River (Horowitz *et al.* 1993). Contaminants from these tailings have washed into the lower Coeur d'Alene River and lake system (Keely *et al.* 1976, Horowitz *et al.* 1993). Waterfowl mortality related to heavy metal poisoning, particularly among tundra swans, was reported in the lower Coeur d'Alene River valley as early as 1924 (Chupp 1956). Other reports by Benson *et al.* (1976), Neufeld (1987), and Blus *et al.* (1991) document more recent waterfowl mortality due to heavy metal poisoning. By quantifying the four wetland plant species, we can learn more about how the ecosystem of the Coeur d'Alene floodplain functions.

METHODS

Three different techniques were used to enhance digital imagery for classification and mapping of the wetland plants. First, image merging of a Landsat TM scene with a SPOT Panchromatic scene of the same date was completed to create an image with higher spectral and spatial resolution. Second, FWS National Wetlands Inventory (NWI) maps (Cowardin 1979) were incorporated as ancillary data. The third technique involved the use of NWI polygons to mask out the upland areas to focus more specifically on the spectral response patterns in the floodplain.

Image Merging

The merge of the SPOT and TM scenes was processed on a Sun Sparc 10 Model 30 workstation with 138 megabytes of swap space and 64 megabytes of RAM. The software used to merge the images was ERDAS Imagine, Version 8.2. To reduce computer processing time, only three of the seven TM bands were processed. TM bands two (green), three (red), and four (NIR) were used for the image merge. This band selection was the default in the ERDAS Imagine software for the Brovay transformation (ERDAS 1994). Brovay transformation was one of several different merging algorithms that could be used in the ERDAS Imagine software. The resampling technique used for the resolution merge was cubic convolution. Cubic convolution recalculates the values for the new cells by using a weighted average of values within a neighborhood of some 25 adjacent pixels (Campbell 1987). ERDAS Imagine software was chosen because it was the only software available that provided image merging techniques. Comparisons of the image resolutions used in the project are found in table 1.

Ancillary Data

Ancillary data can be integrated with remotely sensed imagery to increase the reliability of image classification (Campbell 1987). By using only satellite or remotely sensed images, classification is limited to using only electromagnetic energy as it is reflected from the Earth's

---

Natural Resources Department GIS, Coeur d'Alene Tribe; Department of Forest Resources, University of Idaho, respectively.

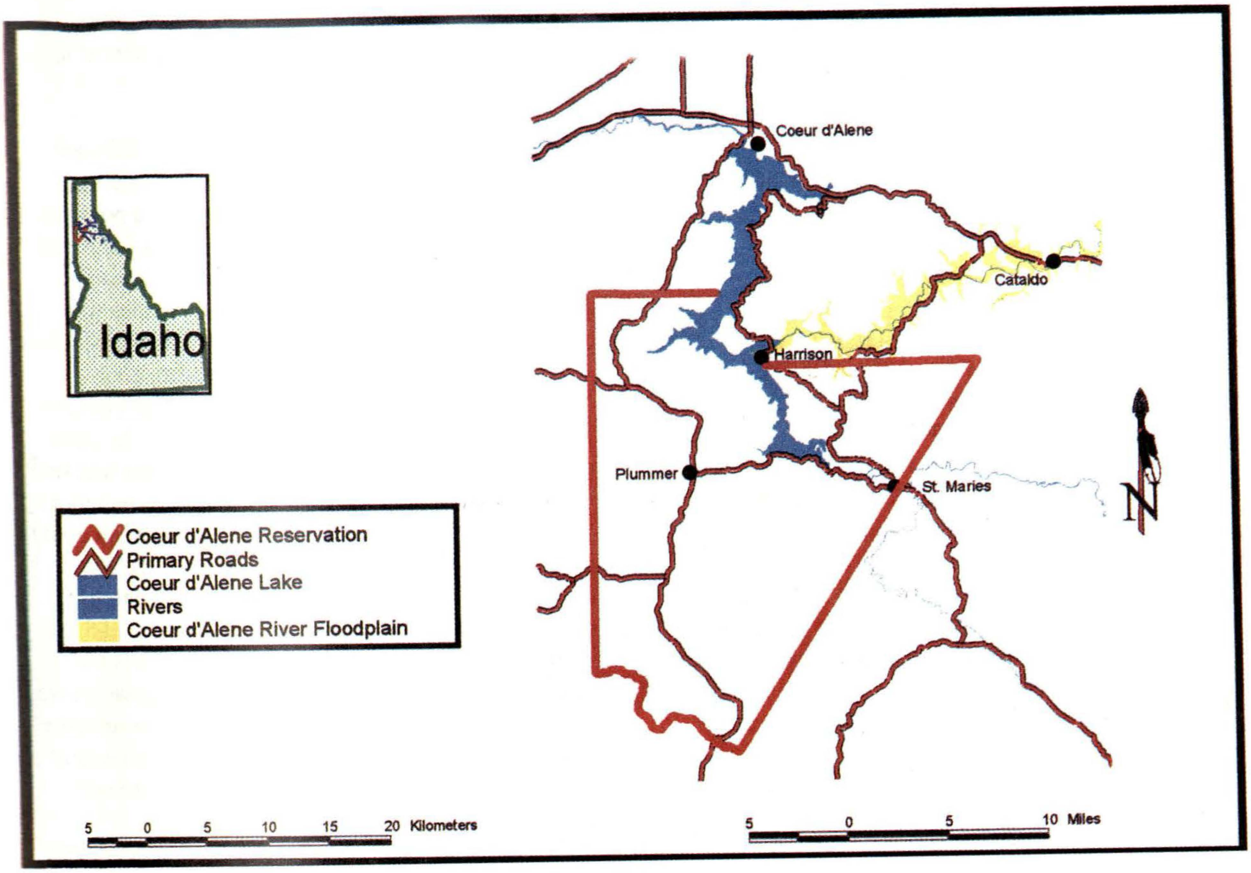

Idaho
Coeur d'Alene
Cataldo
Harrison
Plummer
St. Maries
N
Coeur d'Alene Reservation
Primary Roads
Coeur d'Alene Lake
Rivers
Coeur d'Alene River Floodplain
5 0 5 10 15 20 Kilometers
5 0 5 10 Miles

Figure 1.—*Locations of Coeur d'Alene River floodplain.*

Table 1.—*Comparison of criteria for all image formats used on Coeur d'Alene floodplain project*

Image format	Spatial resolution	Spectral resolution width	Bands	Temporal resolution
	m	*m*	*Number*	*Date*
SPOT Panchromatic	10 x 10	0.22	1	6/18/92
TM	30 x 30	0.08-0.14	7	6/18/92
Merged image	10 x 10	0.08-0.14	3	6/18/92

surface. When observing objects such as plants, reflective responses may change over time due to climate and seasonal growth patterns. However, certain features do not change over the course of the year, such as geologic features, soil types, and wetland habitat types. By integrating data on the distribution of these features with satellite imagery, the analysis algorithms are provided with additional data to aid in classifying the imagery.

Fish and Wildlife Service NWI data (fig. 2) were digitized from 1:24,000 scale maps by the Coeur d'Alene Tribe and the Bureau of Land Management (BLM) for use on the project. This layer was converted to raster format using the Arc/Info POLYGRID command. The grid was exported out of Arc/Info into band interleave by line (BIL) format using the Arc/Info command GRIDIMAGE. The BIL file was then brought into the ENVI image analysis software where they could be joined with the remotely sensed imagery.

Identification of Training Areas

In the process of supervised classification, it is necessary to provide the computer program with site locations of known vegetation. Site locations are known as training areas (Campbell 1987). Either point or polygon-type GIS coverages were developed for each of the four plant species of interest. These data files will be referred to as "training coverages."

Training coverages were compiled using two different methods. The first method used a Trimble Basic Plus resource-grade GPS unit to collect a point or a polygon of the vegetation. Both FWS and BLM field staff assisted the GIS staff in locating large patches of the desired vegetation. Preferred size for vegetation patches was 52.5 x 52.5 m or larger. Patches of this size enabled one pixel (17.5 m) of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) data to be free of edge effect that could be caused by other vegetation (fig. 3). The minimum acceptable patch size for the training data was set to 17.5 m. Analysis of the AVIRIS imagery will be reported elsewhere. In the field notes for the GPS units, an ocular estimate of patch size was recorded. Patch size was useful when selecting training sites on the imagery. Larger homogeneous patches of plants of the preferred size were found only in a few cases. The collection process was difficult because the wetland vegetation was extremely dense. Most of the transportation around the units was done in a canoe or a kayak. In some parts of the marsh, it was physically impossible to move the one-person kayak through the dense plant growth.

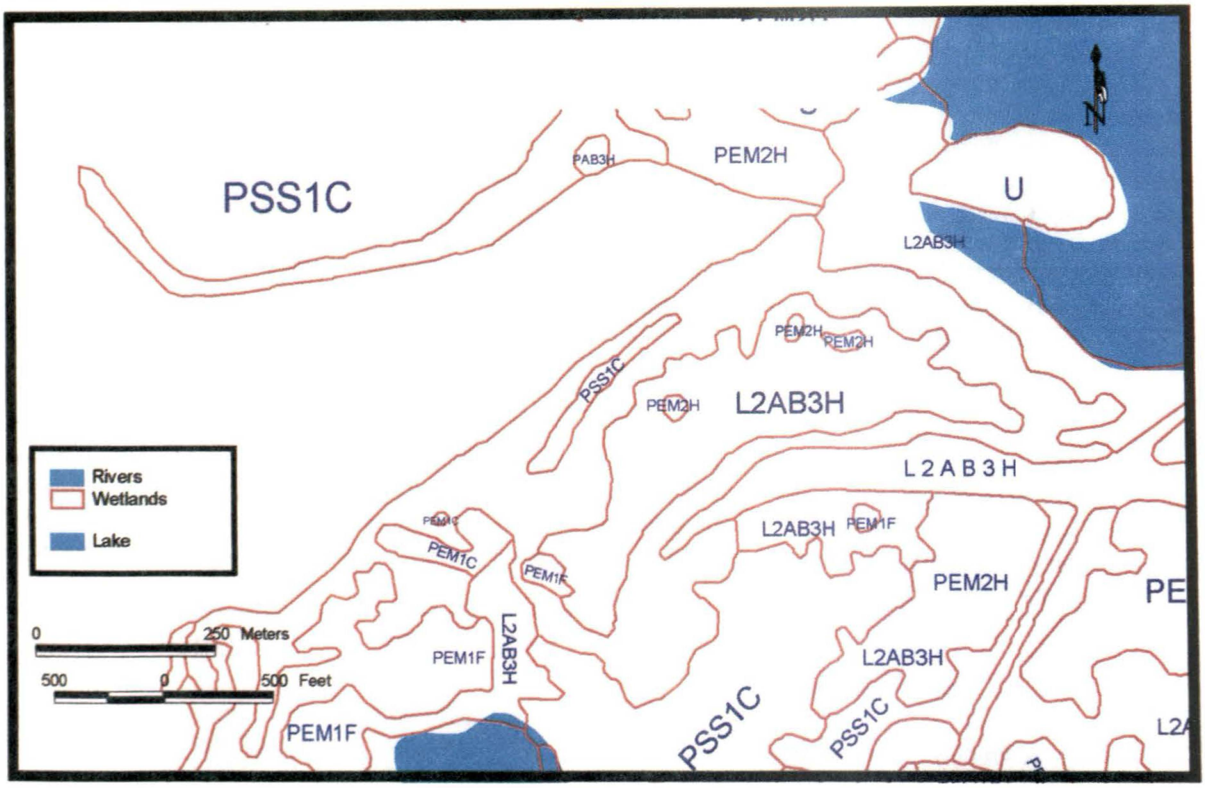


Figure 2.—*Sample National Wetland Inventory (NWI) GIS layer.*

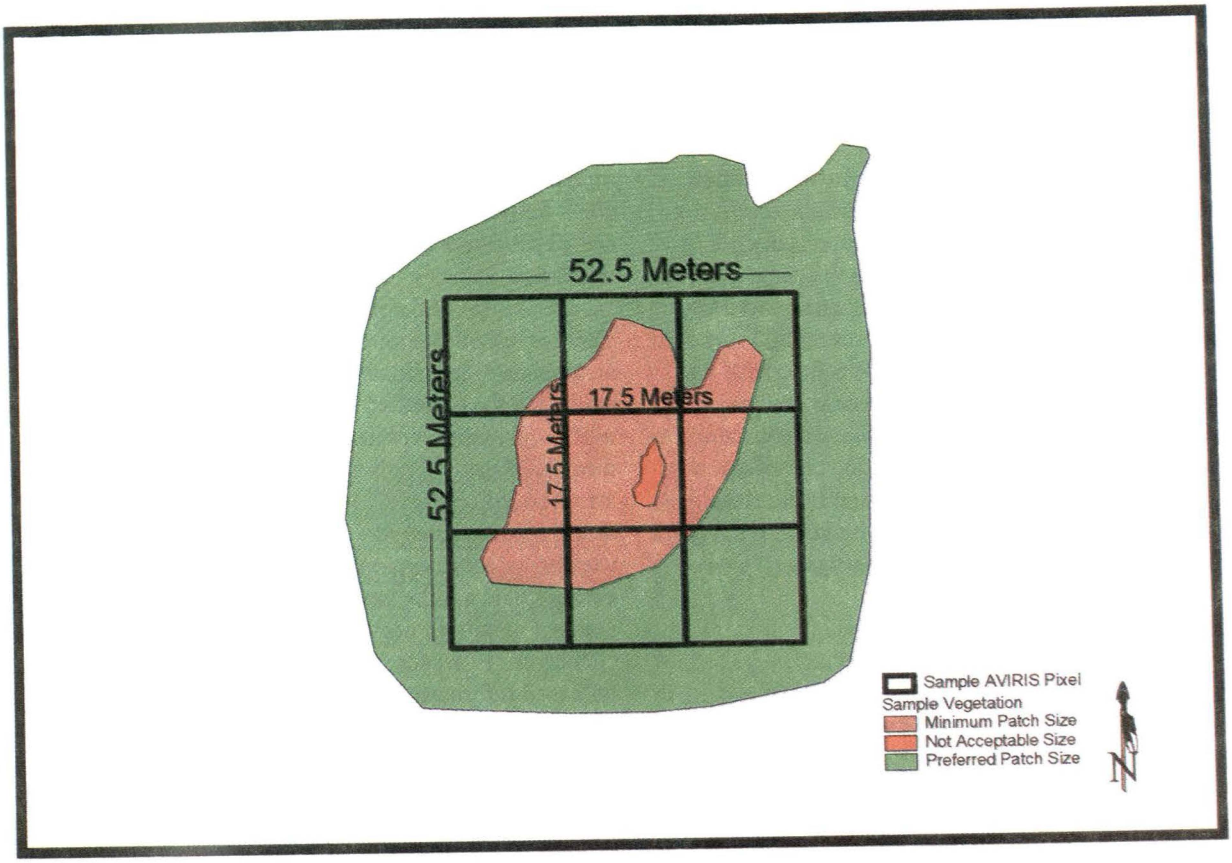


Figure 3.—*Example of AVIRIS 17.5 m pixel size in relation to training site.*

The GPS data were differentially corrected using Trimble's Pathfinder software version 2.5. The accuracy of resource grade GPS after differential correction is stated at 3 to 5 m (Trimble Navigation 1991). Using Arc/Info, the data were then converted into a DXF file format for the ENVI Software. Nine to 18 GPS points of data were collected for each wetland plant species (table 2).

To prepare additional training data, color aerial photographs, along with the images, were manually interpreted to find more potential patches of the desired wetland plants. This process allowed for collection of training data in areas that were inaccessible by field visits. Identifying training data using aerial photos was also done by Butera (1979) in his remote sensing of wetlands in Florida. Creation of additional training data from the aerial photo interpretation was completed using the ENVI software.

Table 2.—*Number of GPS points collected for each plant species*

Plant	Cattail	Horsetail	Wild rice	Water potato
Number of GPS points	12	9	12	18

Image Masking

Non-wetland vegetation was masked out of images to prevent misclassification of vegetation (Ramsey *et al.* 1994). To accomplish this, the FWS National Wetlands inventory GIS layer was used to create a mask of the wetlands. The mask was then used to eliminate any upland areas from the classification implementation.

Image Classification

Digital image classification is a technique that has been demonstrated in the literature to provide accurate classification of wetland vegetation (Butera 1979). The two image classification methods used in this project were the Spectral Angle Mapper (SAM) and the Minimum Distance (MD) classifiers. The SAM method "is a physically-based spectral classification that uses the *n*-dimensional Spectral Angle Mapper to match the reference spectra. The algorithm determines the spectral similarity between two spectra by calculating the angle between the spectra, treating them as vectors in space with dimensionality equal to the number of bands" (ENVI 1996). The

MD technique uses the mean vectors of the combined training sites for a given vegetation class and calculates the Euclidean distance from each unknown pixel to the mean vector (ENVI 1996).

Image analysis was run repeatedly using different input parameters to the MD and SAM classification techniques until a classified image was produced that visually matched the vegetative patterns found on the aerial photos for the study area. Changes in the input parameters increase or decrease (dependent upon the settings) the amount of vegetation identified. The FWS field staff had the greatest knowledge of vegetation types in the project area and therefore served as experts in the evaluation of the output results. Field staff evaluated the classified images from these techniques to determine if the classification matched conditions in the field. Input from FWS staff was then used to refine the image analyses.

Data Field Verification

Once the classified image was produced by the image processing software, the image was converted to an Arc/Info polygon coverage. Arc/Info's IMAGEGRID command was used to import the ENVI BIL file into Arc/Info. The grid was then converted into polygon layers using the GRIDPOLY command. Area and summary statistics for each type of vegetation were then calculated in Arc/Info. The new polygon coverage could then be used by the Arc/View GIS software. To increase the speed of display within Arc/View, the polygon coverage was converted into an Arc/View shape file. Arc/View was then used by the FWS field staff to produce maps of the study areas (fig. 4). These maps were taken to the field for ground validation.

The field verification involved the FWS staff performing an extensive field survey of the project area. The FWS staff used the classified maps in the field and identified where the maps were incorrect. After the field verification, the classified polygons were edited to correct errors based on the FWS expert judgment. Editing the shape files involved re-coding polygons with the correct vegetation code, moving existing polygon lines and vertices, and adding new polygons. This achieved the goals of acquiring accurate information to update the GIS layer. However, it did not provide completely unbiased information to produce a statistical summary of the classified image that came out of the remote sensing software before it was modified for the corrections.

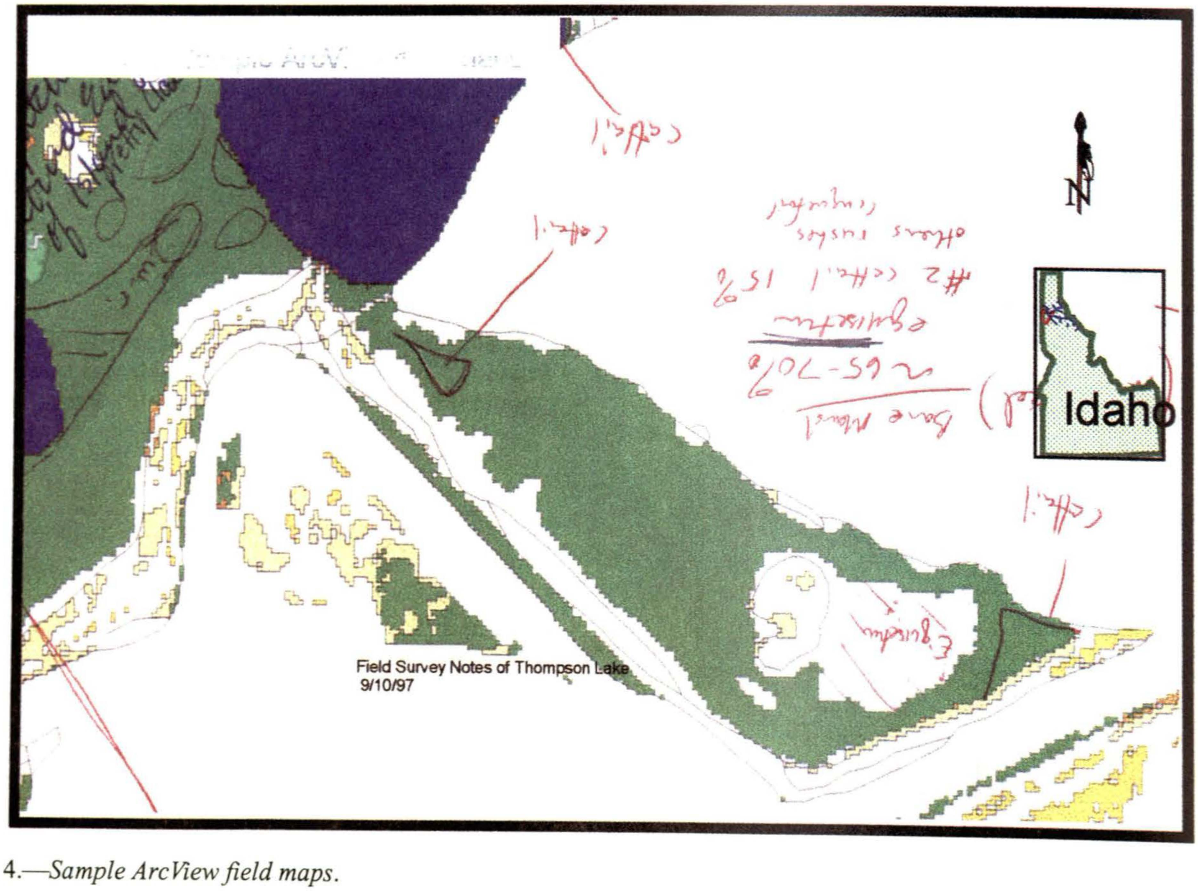


Figure 4.—*Sample ArcView field maps.*

RESULTS AND DISCUSSION

The objective of this research work was to use remotely sensed imagery to map and quantify the wetland plant components of the Coeur d'Alene floodplain ecosystem. At the end of the project this goal was met. The accuracy of the image classification in comparison to the final modified vegetation map made by the FWS was 89 percent correct (table 3). Water horsetail, which was dominant in the ecosystem, had an accuracy of 74 percent correct; less frequent species such as cattail, water potato, and rice had lower accuracies (63, 39, 63 percent, respectively).

Table 3.—*Percent correct on image classification compared to final plant map for each plant species*

Plant	Cattail	Horsetail	Wild rice	Water potato
Percent correct	63	74	63	39

Discussion

The ability to handpick the images for the project may have led to a higher level of accuracy in the final image classification. The analysis of images taken in early summer likely reduced our ability to discriminate some types of vegetation. The initial image classification might have been more accurate if the images had been collected in August when the vegetation was at its maximum phenologic development. In Thompson Lake, one of the floating islands had actually moved to a different part of the marsh in December 1995 (Snyder, M., FWS Biologist, pers. comm., 1998). Hence, the images used for this exercise misidentified the current location of the floating island and had to be corrected in the final wetland plant GIS layer. Images of the floating island that moved in Thompson Lakes are found in figure 5 and figure 6.

Locating homogenous vegetation patches that met the minimum dimension requirements was difficult. Most patches of wetland plants were found in long, narrow strips located along the shoreline. Relatively few of these patches of vegetation met the minimum width of 17.5 m to be used for training sites. In addition, most of the plant species mapped did not occur in homogeneous patches. An example of this is horsetail and water potato, which sometimes grew in together.

The on-ground training site collection provided valuable information that could be used when identifying plant species from aerial photographs. Vegetation types dominated by horsetail and cattail could be easily identified from the photographs, suggesting the utility of aerial photo interpretation for ground truthing in wetlands where access is difficult.

Examination of the images using the spectral plots of the training data revealed additional information about the data set. The NWI wetland delineation showed some degree of correlation with the location of the four plant species. For this reason, it was used as an ancillary band of information throughout the classification process.

Image masking proved to be a very useful technique. One of the benefits was that the geographic area covered by the images was reduced, which reduced the computer file size. Since the file size was reduced for each image, the image-processing speed increased. Image masking may have also increased the accuracy of the image classification.

Both image classification algorithms produced a variety of results. ENVI's SAM algorithm was a method not available with the other remote sensing software packages at the time and was highly recommended by the ENVI software support staff (Fegley, A., ENVI Software Specialist, personal communication, 1996). Yet, after repeated trials, at more than 20 different spectral angle settings, a suitable classification of the data set based on FWS's ocular inspection of the classified images was not found. Repeated tests of the MD algorithm did provide a suitable classification. This method was used in the final classification. A setting of 15 was the final MD parameter entered for the SPOT/TM image, and it seemed to produce the most representative classified image.

Conclusions and Recommendations

Many of the limitations expressed above with the SPOT/TM data may have been overcome if the scenes had been collected when the wetland plants were fully emerged. However, because of the limited 10-m resolution of the imagery, future efforts may be better invested in evaluating finer resolution imagery. One potential imagery source may be the Indian Remote Sensing 1C 5-m imagery. Another option may be to evaluate the use of resolution merging using digital orthophotos and some other form of multispectral data such as SPOT multispectral. With these two image formats, one might create a merged data set with greater spectral and spatial resolution.

Image processing software was one of the limiting factors in the project. Much time was spent in converting data between various software programs and in developing work-arounds for inadequacies in the software. One example: the ENVI software had a utility to export data into Arc/Info format, but the Arc/Info software could not

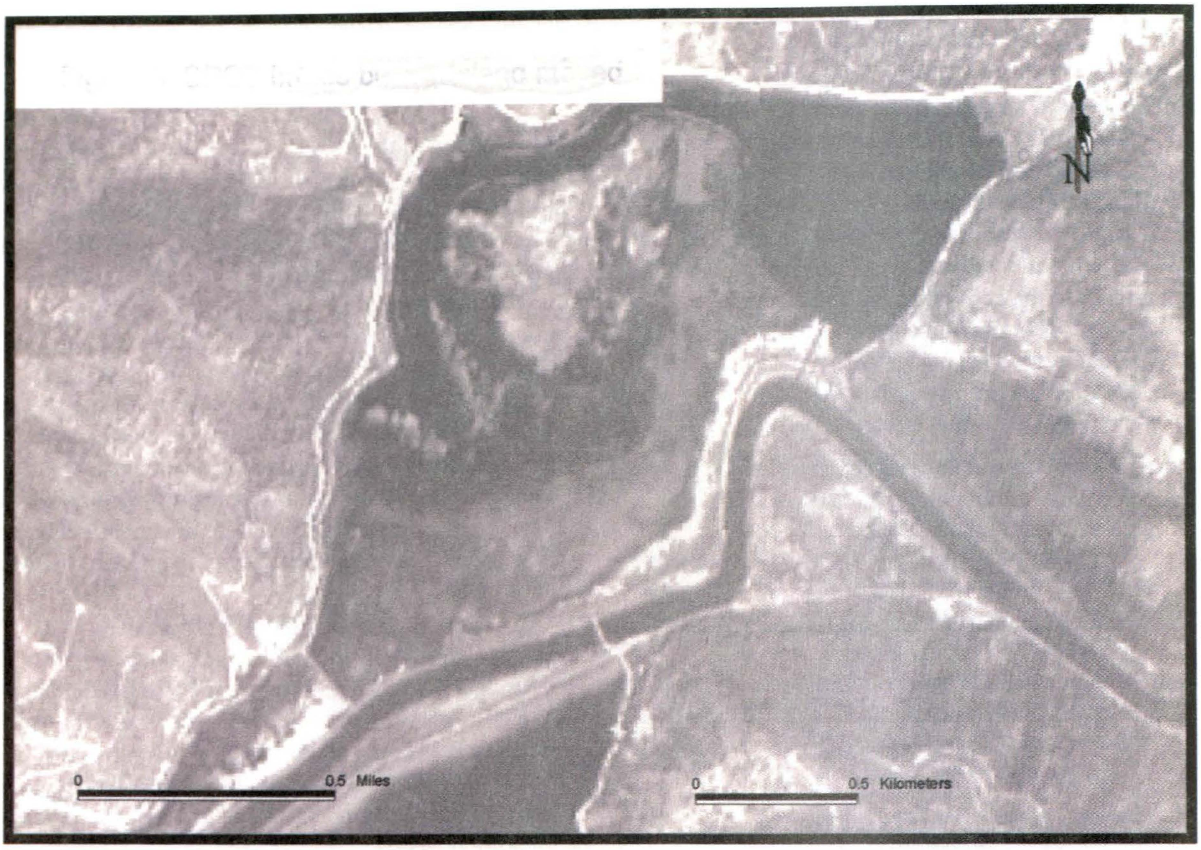

N
0
0.5 Miles
0
0.5 Kilometers

Figure 5.—*SPOT image before island moved.*

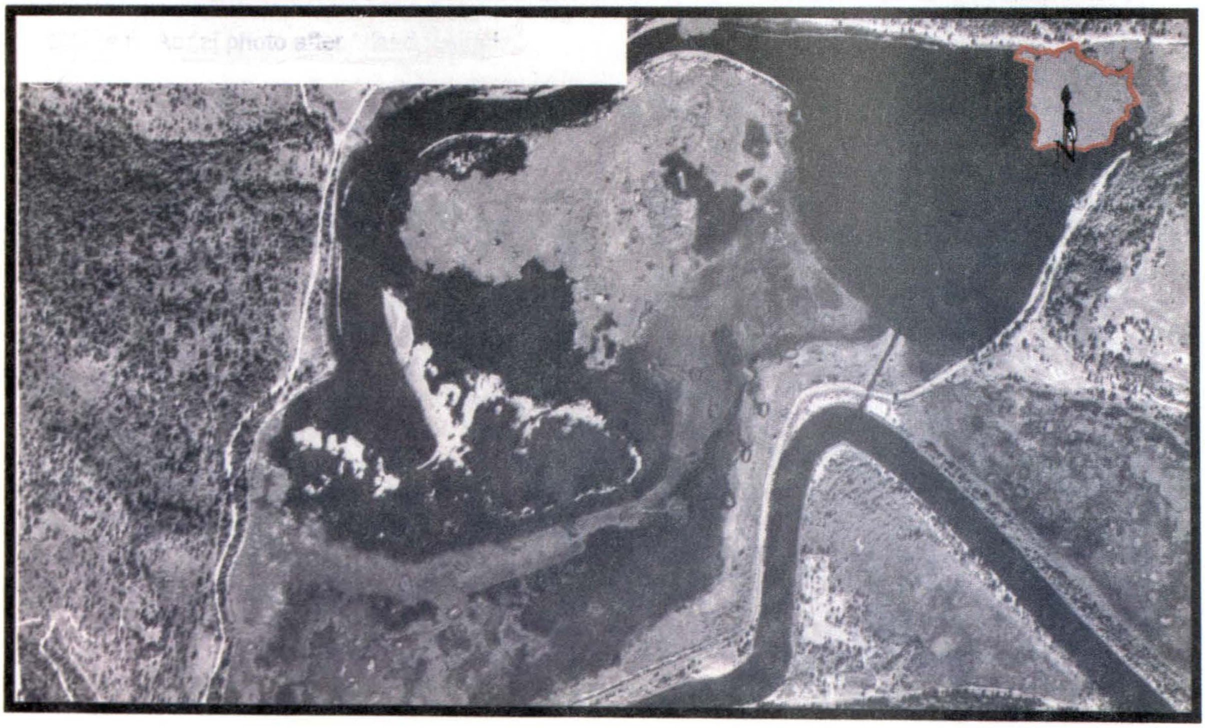


Figure 6.—*Aerial photo after island moved.*

read the "Arc/Info" format data out of ENVI. These barriers should be overcome by new releases of software.

Much of the time spent in this project was used for developing the methods to digitally classify wetland plant species. The authors are not aware of other studies attempting to identify individual wetland plants using any of the above image formats. The process outlined in this research represents only the first step in attempting to identify wetland vegetation, and more refinement and evaluation of the methods are required.

Digital remote sensing is useful in mapping wetland vegetation. As new sensors become available, delineation of individual wetland plant species may become more accurate. At this time, sensors such as SPOT, TM, and AVIRIS have limited spatial resolutions for identifying individual wetland plants. Species that grow in larger homogeneous patches may be mapped more easily than those that grow in small or mixed patches. The diversity and relatively rapid temporal changes that occur seasonally in the Inland Northwest pose great challenges to further attempts for remote sensing of wetland plants. Appropriate sensor selection and temporal criteria are crucial for successful application. These combined factors may determine that it will be possible to map only broader wetland plant community assemblages.

The modified classified image produced in this project should be used and further refined for ecosystem assessment in the Coeur d'Alene River floodplain. The wetland vegetation is just one potential piece of the puzzle required in analyzing the complex ecosystem problems that exist in the Coeur d'Alene floodplain. This layer, when combined with other spatial data such as water flow through the wetlands, animal mortality, and sediment samples, could be an extremely valuable data set for restoration and management planning activities.

ACKNOWLEDGMENTS

The authors thank the Coeur d'Alene Tribe and the U.S. Fish and Wildlife Service field office in Spokane, Washington, for their assistance and cooperation in this study. We would also like to thank Julie Campbell, Mark Snider, and Scott Deeds; without their help, this project would have not been possible. The authors thank Phillip Cernera, Coeur d'Alene Tribe, and Dan Audet and Bob Foley of the USFWS, for review of the manuscript.

LITERATURE CITATIONS

Butera, K.M. 1979. Demonstration of wetland vegetation mapping in Florida from computer processed satellite and aircraft multispectral scanner data. National Aeronautics and Space Administration Tech. Pap. 1553. Washington, DC: National Aeronautics and Space Administration.

Benson, W.W.; Brock, D.W.; Gabica, J.; Loomis, M. 1976. Swan mortality due to certain heavy metals in the Mission Lake area, Idaho. Bulletin of Environmental Contamination and Toxicology. 15: 171-174.

Blus, L.J.; Henny, C.J.; Hoffman, D.J.; Grove, R.A. 1991. Lead toxicosis in tundra swans near a mining and smelting complex in northern Idaho. Archives of Environmental Contamination and Toxicology. 21: 549-555.

Campbell, J.B. 1987. Introduction to remote sensing. New York, NY: The Guilford Press.

Chupp, N.R. 1956. An evaluation of the lower Coeur d'Alene River waterfowl habitat in Kootenai County, Idaho. Moscoe, ID: University of Idaho. 119 p. M.S. thesis.

Cowardin, L.M.; Golet, F.C.; LaRoe, E.T. 1979. Classification of wetlands and deepwater habitats of the United States. Publ. FWS/OBS-79/31. Washington, DC: U.S. Department of the Interior, Fish and Wildlife Service.

ENVI. 1996. ENVI Version 2.5. Boulder, CO: Research Systems, Inc.

ERDAS. 1994. ERDAS Field Guide, 3d ed. Atlanta, GA.

Horowitz, A.J.; Elrick, K.A.; Cook, R.B. 1993. Effect of mining and related activities on the sediment trace element geochemistry of Lake Coeur d'Alene, ID, USA. Part I: Surface Sediments. Hydrology Proceedings. 7: 403-423.

Keely, J.F.; Hutchison, F.I.; Sholley, M.G.; Wai, C.M. 1976. Heavy metal pollution in the Coeur d'Alene Mining District. Proj. Tech. Rep. of Natural Science Foundation Grant No. EPP 75-08500.

Neufeld, J. 1987. A summary of heavy metal contamination in the lower Coeur d'Alene River valley with particular reference to the Coeur d'Alene River Wildlife Management Area. Idaho Department of Fish and Game.

Ramsey, E.W.; Spell, R.E.; Day, R.M. 1994. GIS and remote sensing as wetland resource management tools: the fire monitoring example. In: Proceedings of an International workshop on requirements for integrated geographic information systems; 1994 February 2-3; New Orleans, Louisiana: 133-145.

Trimble Navigation. 1991. Differential correcting the GPS Pathfinder Basic, Factsfinder, 6.

Data Fusion of Landsat TM and IRS Images in Forest Classification

Guangxing Wang, Markus Holopainen, and Eero Lukkarinen

Abstract.—Data fusion of Landsat TM images and Indian Remote Sensing satellite panchromatic image (IRS-1C PAN) was studied and compared to the use of TM or IRS image only. The aim was to combine the high spatial resolution of IRS-1C PAN to the high spectral resolution of Landsat TM images using a data fusion algorithm. The ground truth of the study was based on a sample of 1,020 relascope plots. The results indicated that compared to use of TM or IRS image only, the data fusion increased the classification accuracy of four tree species classes, three age classes, and their 12 combined stand classes. However, the classification using IRS image alone was not better than that using TM images only.

Satellite remote-sensing data can be related to a number of stand-level forest characteristics (Ahern *et al.* 1991; Cihlar *et al.*; 1991, Cook *et al.* 1989; Häme 1984; Poso *et al.* 1984, 1987). These relationships can be used in forest inventories (Franklin 1986, Ripple *et al.* 1991, Sader *et al.* 1989). Small position distortions due to high orbit altitude and large area coverage (e.g., Landsat TM 185 x 185 km) are properties that can also be exploited in forest inventory. However, the spatial resolution of satellite remote-sensing data is too poor to fully capture forest stand parameters with high levels of accuracy (Jupp *et al.* 1988, 1989).

As new satellites are launched, the spatial resolution of images has increased to 5 m in IRS-1C (PAN). In the near future, the resolution will be even 1 m in CARTERRA-1, for example. These new satellites combine high spatial resolution with large area coverage and small positional distortion. Unfortunately, these high spatial resolution data are registered only for the panchromatic channel (e.g., IRS-1C 0.5 - 0.75 µm), while vegetation is interpreted most reliably from multispectral images. Thus, more and more attention has to be paid to how to combine the advantages of both data sources by techniques known as data fusion or data merging. The aim is to combine high spatial resolution of one sensor (e.g., IRS-1C PAN) to the high spectral resolution of another sensor (e.g., Landsat TM).

A great deal of effort has been put into improving remote sensing data for visual image analysis (Cliche *et al.* 1985, Haydn *et al.* 1982). Jaakkola and Hagner (1988) obtained promising results by merging SPOT-1 HRV images to panchromatic aerial photographs. They used the combined images mainly for visual interpretation. Numerical analysis for merged images has also been studied widely (Pradines 1986, Price 1987). Liuha (1996) presented a good overview of these methods.

In the present study, Landsat TM was merged with IRS-IC (PAN). Landsat TM was selected to provide the spectral information, since in various studies it had recorded highly relevant information for vegetation inventories. The present Indian Remote Sensing panchromatic (IRS-1C PAN) image provides 5-m spatial resolution and was thus chosen to produce spatial data. The main objective of the study was to improve classification accuracy of forest stands using image data fusion techniques. The emphasis was put on numerical image analysis with consideration of visual interpretation. The original and merged images were compared. Forest stand was a classified variable defined by main tree species and stand age.

MATERIAL

The Hyytiälä area, located in southern Finland (61°50'N, 24°18'E), was selected for this study. The area was characterized by the presence of mineral soil and pure and mixed coniferous forests of Scots pine *(Pinus sylvestris)* and Norway spruce *(Picea abies)* with managed forest fragments of various ages and soil fertility types. The terrain has low, gently sloping hills, and the average elevation is 155 m above sea level with a range from 140 to 185 m.

The field data consisted of 232 systematically located (100-m x 100-m grid) plots taken during summer 1995 and 788 plots taken in 1989, which were updated to the 1995 level. The total size of the area was about 300 ha.

Guangxing Wang, Postdoctoral Researcher, Department of Natural Resource and Environmental Sciences, University of Illinois, Urbana, IL, USA. E-mail: wang12@uiuc.edu; Markus Holopanen, Researcher, Department of Forest Resource Management, P.O. Box 24, FIN-00014, University of Helsinki, Finland. E-mail: markus.holopainen@helsinki.fi; and Eero Lukkarinen, Researcher, Metsäteho Oy, P.O.Box 194 (Unioninkatu 17), FIN-00131, Helsinki, Finland. E-mail: eero.lukkarinen@metsateho.fi

Tree, site type, and vegetation information were measured on all plots using fixed-area relascope plots (radius of 12.5 m). For a more detailed description of the sampling design and field measurements, readers are referred to Wang (1996). The field plots were geo-referenced using GPS with differential correction and six receiving channels.

Satellite images used included Landsat TM channels 1 - 5 and 7 taken on June 1, 1995, and an Indian Remote Sensing (IRS) panchromatic channel taken on August 24, 1996. The IRS was launched on December 28, 1995, and it revisits the same orbit every 24th day. The orbit altitude of the IRS with three sensors is 817 km, and the sensor PAN provides panchromatic image with spatial resolution of 5 m and spectral resolution of 0.5 – 0.75 μm.

The study area was located in the center-lower part of the IRS and TM images. The IRS panchromatic image and TM images were rectified to the Finnish uniform co-ordinate system using affine transformation with more than 12 control points. The rectification accuracy was 0.58 pixels in the columns and 0.33 pixels in the rows for the TM images, and 1.04 pixels in the columns and 1.51 pixels in the rows for the IRS image. The spatial resolution of the TM image was 30 m, and the spatial resolution of the IRS image was 5 m.

The classification accuracy of the images was computed using a special classification variable, forest stand, by taking into account main tree species and ages of the stand. The main tree species (> 55 percent basal area) included four classes (pine, spruce, deciduous, and mixed), and stand average age consisted of three classes (young stands: < 16 years, middle-aged stands: 16-65 years, and mature stands: > 65 years). Thus, the total number of possible forest stands was 12; however, only 11 classes actually existed in the collected field material (table 1).

The 232 field sample plots measured in 1995 were used to provide ground truth for image classification. The 788 field plots measured in 1989 were updated to the level of 1995 and applied to test the classification accuracy of the forest stands. The data were updated because no independent test samples at the same measurement time were available for the analysis.

METHODS

Study Outline

The study can be divided into three parts: data fusion of the IRS panchromatic channel and six TM channels, classification of sample plots into forest stands, and accuracy assessment of classification. The ER Mapper system (ER Mapper 1995) was applied to the data fusion and unsupervised classification of images by the K-means algorithm. The strata from the unsupervised classification and the field data were combined to derive class estimates for the forest stands. The accuracy of the classification obtained was assessed plotwise using a remote sensing-based forest inventory and monitoring system called SMI, developed by the Department of Forest Resource Management at the University of Helsinki (Poso *et al.* 1984, 1987, 1990; Waite 1993; Wang *et al.* 1997). Figure 1 shows an outline of the study.

Data Fusion

The original images were rectified to the Finnish uniform co-ordinate system (called YKJ) and saved in the data

Table 1.—*List of forest stands used and the respective numbers of field plots*

Main tree species	Age-class	Forest stand		Number of field plots
		Class number	Description	
Pine	1	1	young pine	17
Pine	2	2	middle-aged pine	206
Pine	3	3	mature pine	250
Spruce	2	5	middle-aged spruce	103
Spruce	3	6	mature spruce	269
Deciduous	1	7	young deciduous	20
Deciduous	2	8	middle-aged deciduous	54
Deciduous	3	9	mature deciduous	6
Mixed	1	10	young mixed	15
Mixed	2	11	middle-aged mixed	26
Mixed	3	12	mature mixed	54
Total				1,020

Data fusion

The IRS panchromatic and 6 TM channels

Transformation of images to the ER Mapper format

Merging the images
1) selection of 3 TM channels
2) histogram transformation or Gaussian equalization
3) data fusion by the Brovey-transformation

Unsupervised classification

Setting parameters: e.g.
- channels
- number of classes
- iterations

Classification by K-Means algorithm

Results for each pixel based on window

Accuracy assessment

Division of sample plots to training and test data sets

Calculation of the forest stand mode for each image class using the training data set

Deriving forest stand for each test set sample plot

Accuracy assessment of the test data set
- image class versus field information

Figure 1.—*An outline of the study.*

form used in the ER Mapper. A seven-channel virtual data set containing six TM channels and the IRS panchromatic image was created. The ratio method was chosen for data fusion of TM channels and IRS, because it was known to retain radiometric information. The ratio method is especially suitable for images that correlate strongly (Liuha 1996, Pradines 1986). In the present study, pairwise image correlation coefficients varied between 0.59 - 0.80, regarded as being strong enough. The ratio is a straightforward method to combine spectral information of Landsat TM to the spatial information of the IRS (fig. 2).

When creating a suitable photo for visual interpretation, one should take into consideration that the human eye is sensitive to small changes in structure and to overall color patterns. This indicates that high variability information should be shown as intensity, whereas overall patterns should be shown in color. An algorithm called the Brovey transformation data fusion was created in the ER Mapper using a formula for combining the TM images in red, green, and blue, and the IRS panchromatic image in intensity, further sharpened using a histogram transformation and Gaussian equalization to the IRS image. During this processing, the ER Mapper data remain in the original resolutions of the TM images and the IRS image. When the Brovey transformation algorithm was used for classification, the operation was made based on TM image pixels (30 x 30 m) and the corresponding size window (6 x 6 pixels) of IRS panchromatic image pixels (5 x 5 m). However, the resolution of the classification result image was the same as that of the IRS panchromatic image. The outcome was an image resembling a false color aerial photo.

To create a merged image, one can choose any combination of the TM channels. To present the formulas needed for calculation, an example is given. When TM channels 3, 2, and 1, are selected to be displayed as red, green, and blue, and the IRS panchromatic image is taken in intensity layer, the transformation can be expressed as formulas (1-3):

$$B = \frac{TM_1 * IRS_{PAN}}{TM_1 + TM_2 + TM_3} \qquad (1)$$

$$G = \frac{TM_2 * IRS_{PAN}}{TM_1 + TM_2 + TM_3} \qquad (2)$$

$$R = \frac{TM_3 * IRS_{PAN}}{TM_1 + TM_2 + TM_3} \qquad (3)$$

There are many possible combinations of TM channels.

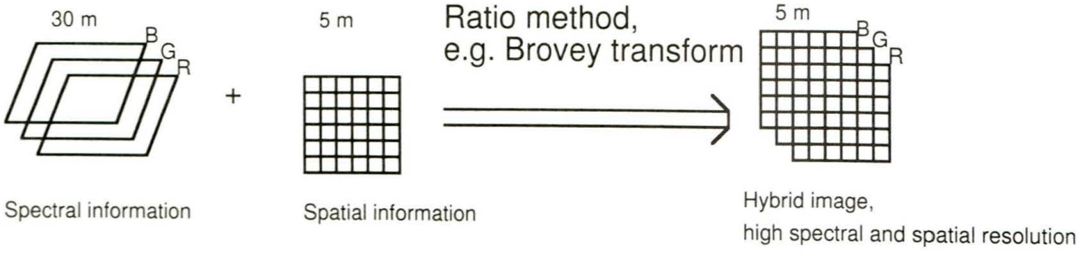


Figure 2.—*Data fusion by e.g. Brovey transform.*

However, the Brovey transformation algorithm was used in this study as a method of data fusion to select and combine TM channels with the IRS panchromatic image so that the resulting image would be simultaneously interpretable visually and numerically. Due to visual interpretation, certain factors had to be taken into account in the fusion process. TM channels are sensitive to certain spectral windows; for example, channel one registers wavelengths 0.45 - 0.52 μm, which the human eye senses as blue. So, for a merged image, the blue layer should preferably be TM channel one, the green channel two, and the red channel three or four. The following combinations were also tested here:

Layer	TM ch	TM ch	TM ch	TM ch	TM ch	TM ch
R	3	4	5	5	5	7
G	2	3	3	4	4	4
B	1	2	1	1	2	1

Either TM channel 3 or 4 was present in all combinations because these channels are known to perform well when estimating biomass or vegetation. For example, the normalized vegetation index (NVDI = (TM4-TM3) / (TM4 + TM3)) has been used in the assessment of forest biomass and other ecological characteristics by remote sensing. (Campbell 1987, Cihlar *et al.* 1991, Sader *et al.* 1989).

Unsupervised Classification

An unsupervised classification of the whole image produced by the Brovey transformation was performed. The classification of each pixel was based on a window of 30 x 30 m for the merged images with resolution of 5 m. For comparison, an unsupervised classification of the TM channel combinations or the IRS panchromatic image only was also carried out. In the unsupervised classification, one of the most important input parameters was number of classes. The processed image area mainly consisted of forested land, agricultural land, waste land, built-up area, lakes, and roads. Forested land was further classified into forest stands, and the maximum number of those classes was 11. Thus, the number of classes for the classification of the processed image area was set to 20. In addition, the default values of the ER Mapper for the number of iterations (9999) and unchanged percent (98 percent) were used as the respective input parameters.

Plotwise Accuracy Assessment

The plotwise accuracy of the classification was assessed using the SMI system. Although the whole image area also included other land-use classes, the emphasis for the assessment was put upon the classification of the forest stands shown in table 1. Field data were divided into two parts: (a) training data set (232 sample plots), and (b) test data set (788 sample plots). The training data set was used to define forest stand for each image class. This was done simply by attaching the most frequent forest stand class in the field to each image class. The forest stands of the training plots and these image classes were combined resulting in an image with known class contents. The estimate of forest stands for a sample plot in the test data set was derived using the most frequent forest stand class within the window of 30 x 30 m around the plot center in the result image of 5-m resolution.

Assessment of classification accuracy was based on an error matrix, in which the estimated and observed stand classes at the test plots were compared. In the error matrix, the diagonal elements show the number of correctly classified observations. The percentage correct, which is mostly used to evaluate the estimation accuracy, is calculated by dividing the number of correctly classified observations by the total number of observations. The percentage correct shows only the relative effectiveness of the classification; it does not account for the entire error matrix, i.e., the estimation accuracy of each individual class. Cohen (1960) improved the analysis of an error matrix and developed a new estimator referred to as the Kappa value. Kappa (Formula 4) is a measure for quantifying the agreement between estimated and observed classes.

$$K = \frac{observed - \exp ected}{1 - \exp ected} \tag{4}$$

Observed indicates the overall percentage correct value and *expected* indicates the estimate of chance agreement. *Expected* is calculated by first assigning the products of the row and column totals to each cell of the matrix, after which the diagonal values are summed and divided by the grand total of the products. A Kappa value of 1.0 indicates a perfect, and 0 or less, a poor classification result. Values near zero imply that the classification is not significantly better than a random assignment of observations to classes.

RESULTS

The resolution difference between IRS-1C PAN and Landsat TM channel 4 is shown in figure 3. There is also a merged image that has spectral information for TM channels 2, 3, and 4 presented as blue, green, and red. To the resulting image, IRS-1C PAN was added as intensity information. The image can be regarded as being more suitable for visual interpretation than TM or IRS image alone. However, its suitability to digitizing, compartment boundaries, for example, was not tested.

The numerical analysis started with the unsupervised classification of the merged images. The resolution of the classified images increased from 30 by 30 m of TM images to 5 by 5 m of the IRS-1C PAN image. The classified images should thus be more detailed, and they should contain more information. Figure 3 gives an example of one merged image (TM4, TM3, TM2, IRS) classified to the present age classes.

The plotwise accuracy was assessed calculating error matrices between the image classification results and field measurements of the forest stands. The performances of the merged images, TM and IRS-1C PAN images, were compared by percentage correct and Kappa values (table 2).

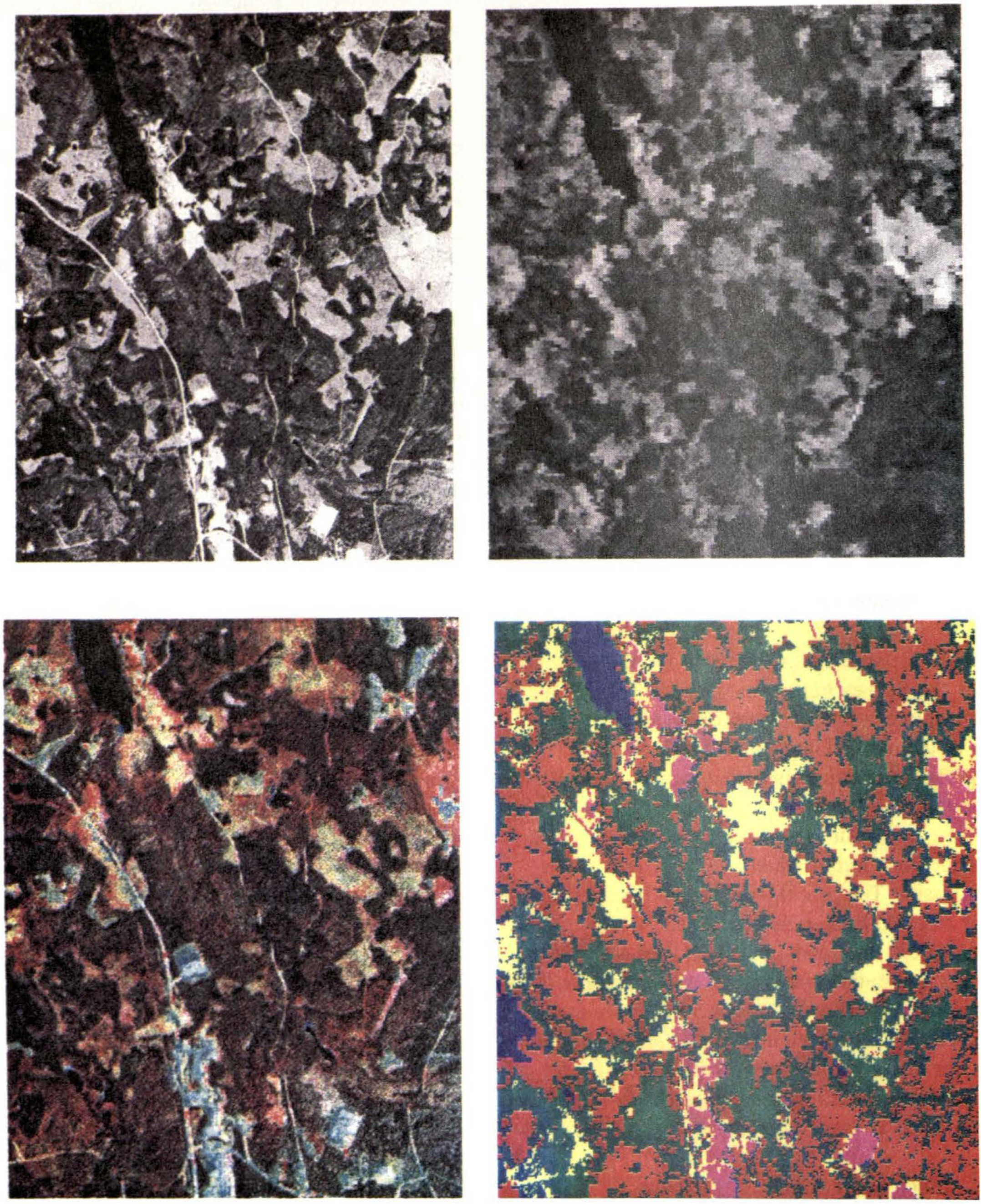


Figure 3.—*IRS-1C PAN (above left), Landsat TM4 (above right). Merged image of TM2 - blue, TM3 - green, TM4 - red and IRS-1C PAN - intensity (below left). Below right same image classified. Blue - water, Red - mature stands, Green - middle-aged stands, Yellow - young stands, and Magenta - others. These colors corresponding following grays: blue = black, red = dark gray, green = light gray, yellow = white, magenta = light dark gray.*

Table 2.—*Plot wise classification accuracy for forest stands*

Data fusion of TM and IRS			TM or IRS		
Image	Percentage correct, %	Kappa value	Image	Percentage correct, %	Kappa value
		4 tree species classes			
TM432_I	56.7	0.277	TM432	50.7	0.219
TM531_I	**70.2**	**0.464**	TM531	**67.3**	**0.415**
TM541_I	67.6	0.435	TM541	66.6	0.413
TM741_I	46.2	0.019	TM741	59.6	0.303
			IRS	59.3	0.284
		3 age classes			
TM432_I	**68.5**	**0.356**	TM432	60.1	0.116
TM531_I	56.5	0.201	TM531	57.2	0.180
TM541_I	65.4	0.303	TM541	60.0	0.093
TM741_I	64.3	0.230	TM741	**62.7**	**0.278**
			IRS	61.0	0.206
		12 forest stands			
TM432_I	42.6	0.239	TM432	33.8	0.130
TM531_I	43.5	0.240	TM531	**43.5**	**0.229**
TM541_I	**46.3**	**0.283**	TM541	39.6	0.198
TM741_I	40.4	0.209	TM741	40.2	0.205
			IRS	40.9	0.189

For four tree species classes, the percentage correct was 46.2 - 70.2 percent and the Kappa value was 0.019 - 0.464 when merged images were used. If the TM channels alone were used, the accuracy decreased slightly: 50.7 - 67.3 percent and 0.219 - 0.415 Kappa value. When the IRS image was used alone, 59.3 percent correct and 0.284 Kappa value were obtained. The merged image of TM channels 5, 3, and 1 and IRS gave the best classification accuracy of 70.2 percent correct and 0.464 Kappa value.

For three age classes, the merged images were again slightly better with 56.5 - 68.5 percent correct and 0.201 - 0.356 Kappa value. In the TM channels alone, the corresponding results were 57.2 - 62.7 percent correct and 0.093 - 0.278 Kappa value, and in IRS panchromatic image only, 61.0 percent correct and 0.206 Kappa value.

Finally, 12 forest stand classes were estimated, and it was observed that different combinations of channels led to results having remarkably less variation than species groups or age classes. The merged images were again a bit better with 40.4 - 46.3 percent correct and 0.209 - 0.283 Kappa value. For the TM images alone, the results were 33.8 - 43.5 percent correct and 0.130 - 0.229 Kappa value, and for the IRS image only, 40.9 percent and 0.189.

The IRS panchromatic image provided almost as good a result as TM channels only when estimating age class. It received a 61.0 percent correct compared to 62.7 percent obtained by the best TM combination. With 12 forest stands the difference was a bit larger, and tree species groups' recognition with IRS led to the widest gap to TM.

For all studied combinations except the two—TM741_I for tree species and TM531_I for age classes—combining IRS with TM gave better classification accuracy. The improvement varied from 0.2 to 16.6 in percent correct and from 0.004 to 0.343 in Kappa value. In most cases the relative increase was more than 10 percent.

The following error matrix (table 3) shows the results of tree species detection using the best merged image (TM5, TM3, TM1, IRS). The percentage correct is promisingly good, 70.2 percent. One problem with the method is that one can easily notice the tendency in image classification towards dominating species in the study area. According to the image classification, there are only coniferous species, i.e., pine and spruce. Deciduous and mixed stands almost always contain some pine and spruce, which makes the classification more difficult. Four sample plots of test data were classified to a stratum without any field information in the modeling data set.

According to definitions, there were three age classes, but in the test data all sample plots except one were either middle-aged or mature stands. For the best combination (TM4, TM3, TM2, IRS), the percentage correct was 68.5 (table 4).

The third error matrix presents the classification accuracy of 12 forest stands (table 5). Percentage correct for middle-aged pine and mature spruce stands was more than 80 percent, whereas all the other forest stand classes remained less than 15 percent. Again the tendency towards pine and spruce can be seen, but there are also shifts from pine to spruce and vice versa. Another remarkable thing is that in one species group, age class seems to be difficult to estimate from the image.

Table 3.—*Error matrix for classification of tree species groups*

Ground truth	Classification result							
	Pine	Spruce	Deciduous	Mixed	Correct classfic.	Total	Percent	Kappa
Pine	**316**	51	0	0		367	86.1	0.174
Spruce	86	**234**	0	0		320	73.1	0.158
Deciduous	31	10	**0**	0		41	0	0
Mixed	31	25	0	**0**		56	0	0
Total	464	320	0	0	**550**	784	70.2	0.464

Table 4.—*Error matrix for classification of age classes*

Ground truth	Classification result						
	Young	Middle-age	Mature	Correct. classif.	Total	Percent	Kappa
Young	**0**	1	0		1	0	0
Middle-age	10	**184**	107		301	61.1	0.099
Mature	8	122	**355**		485	73.2	0.14
Total	18	307	462	**539**	787	68.5	0.356

Table 5.—*Error matrix for classification of forest stands*

Ground truth	Classification result													
	1	2	3	4	5	6	7	8	9	10	11	12	Total	P[1]	K[2]
1	**0**	1	0	0	0	0	0	0	0	0	0	0	1	0.0	0
2	0	**134**	6	0	0	23	1	3	0	0	0	0	167	80.2	0.088
3	1	108	**30**	0	0	58	2	2	0	0	0	0	201	14.9	0.022
4	0	0	0	**0**	0	0	0	0	0	0	0	0	0	0.0	0
5	1	23	6	0	**0**	48	2	4	0	0	0	0	84	0.0	0
6	1	32	5	0	0	**200**	0	0	0	0	0	0	238	84.0	0.128
7	0	0	0	0	0	0	**0**	0	0	0	0	0	0	0.0	0
8	0	22	3	0	0	7	3	**1**	0	0	0	0	36	2.8	0.001
9	0	1	0	0	0	3	0	1	**0**	0	0	0	5	0.0	0
10	0	0	0	0	0	0	0	0	0	**0**	0	0	0	0.0	0
11	0	2	2	0	0	9	0	2	0	0	**0**	0	15	0.0	0
12	0	11	0	0	0	28	2	0	0	0	0	**0**	41	0.0	0
												365			
Total	3	334	52	0	0	376	10	13	0	0	0	0	788	46.3	0.283

[1] P = Percentage correct, 2. K = Kappa value

DISCUSSION AND CONCLUSIONS

In the present study, the Brovey data fusion algorithm was used to merge TM and IRS images, and the plotwise accuracy of original and merged images was determined. It appears that resulting images can be interpreted visually without difficulties for many purposes in forestry. Numerical analysis was performed for classified variables, and it was shown that merged images slightly improved the classification result of forest stands compared to the TM or IRS alone.

Although the emphasis of this study was put upon numerical classification, the need for visual interpretation was considered. When TM channels were selected for the data fusion, the selection limitation was not avoided. In fact, the experiment of merging all six TM channels and the IRS image was also carried out and the results for numerical classification were not as good as expected, but similar to the best ones listed in table 2. The main reason may be that high correlation between these TM channels existed and adding more channels did not bring more and useful information.

Holopainen and Wang (1998) obtained better results with the same variables and same field material. They used digitized aerial photographs calibrated using empirical regression technique to minimize problems caused mainly by central projection of the photos. The percentage correct for classifying 12 forest stands was 49.2 compared to the 46.3 percent in the present study. Furthermore, Holopainen (1998) used imaging spectrometer (CASI) data to estimate the same forest stand classes and obtained a percentage correct of 62.2. When comparing the results, however, it must be stressed that the number of sample plots differed from the present study.

It appears that when using the combination of IRS and Landsat TM, one should not expect to gain major improvement in numerical classification of forest stands compared to the IRS or TM images alone. It can also be noted that with CASI and digitized aerial photos, it is possible to produce more accurate results than with merging TM and IRS images. Compared either to digitized aerial photos or an imaging spectrometer, the spatial resolution of IRS-1C PAN is poorer. The spectral resolution of Landsat TM is poorer than CASI data but better than digitized aerial photos. It remains uncertain which of these two is responsible for the poorer classification accuracy. In the near future, new satellites with better spatial resolution will be launched and these questions might be answered.

It is possible that merging the images does not bring additional information compared to the two original images. Another reason for the relatively small improvement obtained merging TM and IRS images may be the small variation among the forest stands in the study area. If the forest was more heterogeneous, the advantage of increasing spatial resolution of fused images may be greater. The usefulness of high resolution images would also be evident when trying to estimate tree-level forest characteristics. The increased spatial resolution of future satellite images may make also this objective possible.

One way to improve the results obtained here would be to reject the classification-based approach. Information on variation is lost when continuous variables are forced into discrete classes. In addition, the basic K-means algorithm labels the training plots only to one class. Similarly, variation is decreased when only the most frequent forest stand class in the field is used to define forest stand to each image class.

Furthermore, some of these problems could be avoided by using fuzzy information presentation instead of classical set theory. The use of fuzzy sets in accuracy assessment expands the amount of information that can be provided about the forest (Gopal and Woodcock 1994). The main idea of the method is that a unit can be a member of multiple categories; i.e., instead of choosing the most frequent stand class, the unit would be connected to several classes. Applying fuzzy technology is believed to lead to more accurate classification results compared to the traditional methods (Gopal and Woodcock 1994).

In Finland, the major forest owners (Enso, Metsähallitus, Metsäliitto, and UPM-Kymmene) are shifting toward systems where total inventories of forests are replaced by continuous updating of forest databases. Since these companies are managing their forests by compartments, one major issue concerning the reliability of an updated database is the correct location of the compartment boundaries. Numerical change detection has been studied widely in Finland. Häme (1991) found that by comparing temporally different Landsat TM image pairs for the same area, changes in forests, especially clearcut areas, can be detected. Häme also pointed out that changes for large areas are detected reliably; however, for small areas, accuracy is poor. Varjo (1993) found that positional errors of compartment boundaries when using numerical change detection could be even several pixels. Hyppänen *et al.* (1996) found digitized aerial photographs to be useful for detecting compartment boundaries of clearcut areas. However, high resolution satellite images or merged images could turn out to be more accurate than low resolution satellite images and more efficient than aerial photographs in performing visual and numerical change detection in forests.

ACKNOWLEDGMENTS

This study is part of the project "Remote sensing in mapping forest bio-diversity." The authors wish to thank the Finnish Culture Foundation, the Ministry of Agriculture and Forestry, and the Graduate School Program in Forest Ecology of the Universities of Helsinki and Joensuu for providing financial support for the study. The authors also express sincere gratitude to the following people who reviewed this manuscript: Simo Poso, Department of Forest Resource Management, University of Helsinki, Helsinki, Finland; Arto Vuorela, Satellite Image Centre of National Land Survey, Helsinki, Finland; and Mark-Leo Waite, Tekla Ltd, Espoo, Finland.

LITERATURE CITED

Ahern, F.J.; Erdle, T.; Maclean, D.A; Kneppeck, I.D. 1991. A quantitative relationship between forest growth rates and Thematic Mapper reflectance measurements. International Journal of Remote Sensing. 12: 378-400.

Campbell, J.B. 1987. Introduction to remote sensing. New York, London: The Guilford Press.

Cihlar, J.; St.-Laurent, L.; Dyer, J.A. 1991. Relation between the normalized difference vegetation index and ecological variables. Remote Sensing of Environment. 35: 279-298.

Cliche, G.; Bonn, F.; Teillet, P. 1985. Integration of the SPOT panchromatic channel into its multispectral mode for image sharpness enhancement. Photogrammetric Engineering and Remote Sensing. 51: 311-316.

Cohen, J. 1960. A coefficient of agreement for nominal scales. Educational and Psychological Measurement. 20: 37-46.

Cook, E.A.; Iverson, L.R.; Graham, L.R. 1989. Estimating forest productivity with Thematic Mapper and biogeographical data. Remote Sensing of Environment. 28: 131-141.

ER Mapper 5.0. 1995. Application, Reference, and Tutorial. Earth Resource Mapping Pty.Ltd.

Franklin, J. 1986. Thematic mapper analysis of coniferous forest structure and composition. International Journal of Remote Sensing. 7: 1287-1301.

Gopal, S.; Woodcock, C. 1994. Theory and methods for accuracy assessment of thematic maps using fuzzy sets. Photogrammetric Engineering and Remote Sensing. 60: 181-188.

Haydn, R.; Dalke, G.W.; Henkel, J.; Bare, J.E. 1982. Application of the IHS color transform to the processing of multisensor data and image enhancement. Proceedings International Symposium Remote sensing of arid and semi-arid lands; Cairo: 599-616.

Holopainen, M. 1998. Forest habitat classification by CASI airborne measurements. Forest and Landscape Research. in press.

Holopainen, M.; Wang, G. 1998. Accuracy of digitized aerial photographs for assessing forest habitats at plot level. Scandinavian Journal of Forest Research. 13(4): 500-509.

Hyppänen, H.; Pasanen, K.; Saramäki. J. 1996. Päätehakkuiden kuviorajojen päivitystarkkuus. Folia Forestalia. (in Finnish).

Häme, T. 1984. Landsat-aided forest site type mapping. Photogrammetric Engineering and Remote Sensing. 50: 1175-1183.

Häme, T. 1991. Spectral interpretation of changes in forest using satellite scanner images. Acta Forestalia Fennica 222. 111 p. ISBN 951-651-092-2.

Inkinen, M. 1997. Numeerisen ilmavalokuvan ja profiloivan tutkan soveltuvuus puustotunnusten kuvioittaiseen arviointiin. The applicability of digital aerial photographs and radar-derived stand profiles to the estimation of stand-wise characteristics. Helsinki University of Technology. 74 p. M.S. thesis (in Finnish with English summary).

Jaakkola, S.; Hagner, O. 1988. Multi-sensor remote sensing for forest monitoring. Proceedings of the IUFRO Subject Group 4.02.05. Meeting in Finland; 1988 August 29- September 2; Helsinki, Finland. Helsinki, Finland: University of Helsinki, Department of Forest Mensuration and Management, Research Notes 21: 146-157.

Jupp, D.L.; Strahler, A.H.; Woodcock, C.E. 1988. Autocorrelation and regularization in digital images I: Basic theory. IEEE Transactions on Geo-science and Remote Sensing. 26: 463-473.

Jupp, D.L.; Strahler, A.H.; Woodcock, C.E. 1989. Autocorrelation and regularization in digital images II: Simple image models. IEEE Transactions on Geoscience and Remote Sensing. 27: 247-258.

Liuha, P. 1996. Image fusion, combining spectral and textural features for improving image analysis. Department of Physics, University of Jyväskylä. (in Finnish with English abstract). 116 p.

Poso, S.; Häme, T.; Paananen, R. 1984. A method of estimating the stand characteristics of a forest compartment using satellite imagery. Silva Fennica. 18: 261-292.

Poso, S.; Paananen, R.; Similä, M. 1987. Forest inventory by compartments using satellite imagery. Silva Fennica. 21: 69-94.

Poso, S.; Karlsson, M.; Pekkonen, T.; Härmä, P. 1990. A system for combining data from remote sensing, maps, and field measurements for forest planning purposes. Helsinki, Finland: University of Helsinki, Department of Forest Mensuration and Management. Research Notes 23.

Pradines, D. 1986. Improving SPOT images size and multispectral resolution. SPIE Vol. 660, Earth Remote Sensing Using the Landsat TM and SPOT Sensor Systems.

Price, J.C. 1987. Combining panchromatic and multispectral imagery from dual resolution satellite instruments. Remote Sensing of Environment. 21: 119-128.

Ripple, W.J.; Wand, S.; Isaacson, D.L.; Paine, D.P. 1991. A preliminary comparison of Landsat Thematic Mapper and SPOT-1 HRV multispectral data for estimating coniferous forest volume. International Journal of Remote Sensing. 12: 1971-1977.

Sader, S.A.; Waide, R.; Lawrence, W.T.; Joyce, A.T. 1989. Tropical forest biomass and successional age class relationships to a vegetation index derived from Landsat TM data. Remote Sensing of Environment. 28: 143-156.

Varjo, J. 1993. Controlling continuously updated forest data by satellite remote sensing. Thesis for licentiate degree in forest management planning, University of Joensuu. 66 p.

Waite, M-L. 1993. Documentation of the SMI/92 forest management planning system. Helsinki, Finland: University of Helsinki, Department of Forest Resource Management.

Wang, G. 1996. An expert system for forest resource inventory and monitoring in the frame of multi-source data. Helsinki, Finland: University of Helsinki, Department of Forest Resource Management. Publications 10. 173 p. Ph.D. dissertation. ISBN 951-45-7289-0.

Wang, G.; Waite, M-L.; Poso, S. 1997. SMI user's guide for forest inventory and monitoring. Helsinki, Finland: University of Helsinki. Department of Forest Resource Management. Publications 16. 336 p. ISBN 951-45-7841-4.

A Comparison Between ERS-1, JERS-1, and Radarsat-1 Radar Satellite Imaging Systems and Landsat MSS & TM and Spot Optical Satellite Imaging System to Detect and Monitor Mangrove Deforestation in East Kalimantan, Indonesia

Mahfud M. Zuhair, Yousif Ali Hussin, and Michael Weir

Abstract.—Mangrove forests are one of the primary features of coastal ecosystems throughout the tropical and subtropical regions of the world. Mangroves are very sensitive and fragile resources, and the pressures of increasing population, food production, and industrial and urban development have caused a significant proportion of the world's mangroves to be destroyed. Reliable and timely information is required to manage the remaining mangrove resources. This paper describes a research project to compare the ability of three different radar satellite imaging systems and three different optical satellite systems to detect mangrove deforestation in the delta of the Mahakam River, East Kalimantan, Indonesia.

Mangrove forests are one of the primary features of coastal ecosystems throughout the tropical and subtropical region of the world. They are biologically diverse and have been used for food resources, firewood, charcoal, timber, and other minor products. However, mangroves are very sensitive and fragile resources; restoring damaged mangroves to their original condition requires much effort and time. In recent years the pressures of increasing population, food production, and industrial and urban development have caused a significant proportion of the world's mangrove resource to be destroyed. As the population has risen, the shortage of productive land in coastal regions of the tropics has resulted in the conversion of mangrove swamps to agricultural purposes and to fish and shrimp ponds for commercial production.

Because it is an archipelago, Indonesia has a large area of mangrove (4,250,000 ha are found around the four main islands). There are basically six categories of land use in the mangrove areas: (1) forest reserves, (2) nature conservation, (3) protection forest, (4) production forest, (5) fish/shrimp ponds, and (6) salt production areas. Mangrove forests are traditionally a source of livelihood for the local population. Therefore, the main problems of managing these resources are delineating the area, resolving local community ownership issues.

Information is crucial to assess mangrove deforestation and to monitor the existing mangrove forests for sustainable management. Because of the particular forest structure, composition, and difficult accessibility of mangrove forests, the task of collecting the information by terrestrial/ground inventory is extremely difficult, time consuming, and therefore very expensive. For this reason, remote sensing is an attractive means of obtaining data for defining deforested areas and updating management plans. A serious drawback to using optical satellite images alone for monitoring mangroves in Indonesia has been the unavailability of cloud-free images at the time of interest. The advent of radar systems is expected to resolve this problem. Unlike optical systems, radar systems can be operated day or night; they also have all-weather capability and can therefore penetrate clouds cover, fog, rain, and atmospheric dust. Furthermore, radar energy can penetrate crops and forest canopies and some surface features (dry sand). The objective of this research was to compare the ability of three different radar satellite imaging systems (i.e., ERS-1, JERS-1, and Radarsat) and three optical satellite data (i.e., Landsat TM, MSS, and Spot XS) to detect mangrove deforestation in the delta of the Mahakam River, East Kalimantan, Indonesia.

MATERIALS AND METHODS

The following data were used in this research project: Landsat MSS of 1983, Landsat TM of 1994, and SPOT XS of 1987. Radar data used were from ERS-1 of 1996, JERS-1 of 1996, and Radarsat of 1997. The research methodology is illustrated in figure 1.

Lecturer at the School of Forestry, University of Mulawarman, Samarinda, East Kalimantan, Indonesia; and Assistant Professors at the International Institute for Aerospace Survey, and Earth Science (ITC), 7500 AA, Enschede, The Netherlands, respectively. Fax (31)53-4874-399; E-mail HUSSIN@ITC.NL, WIER@ITC.NL.

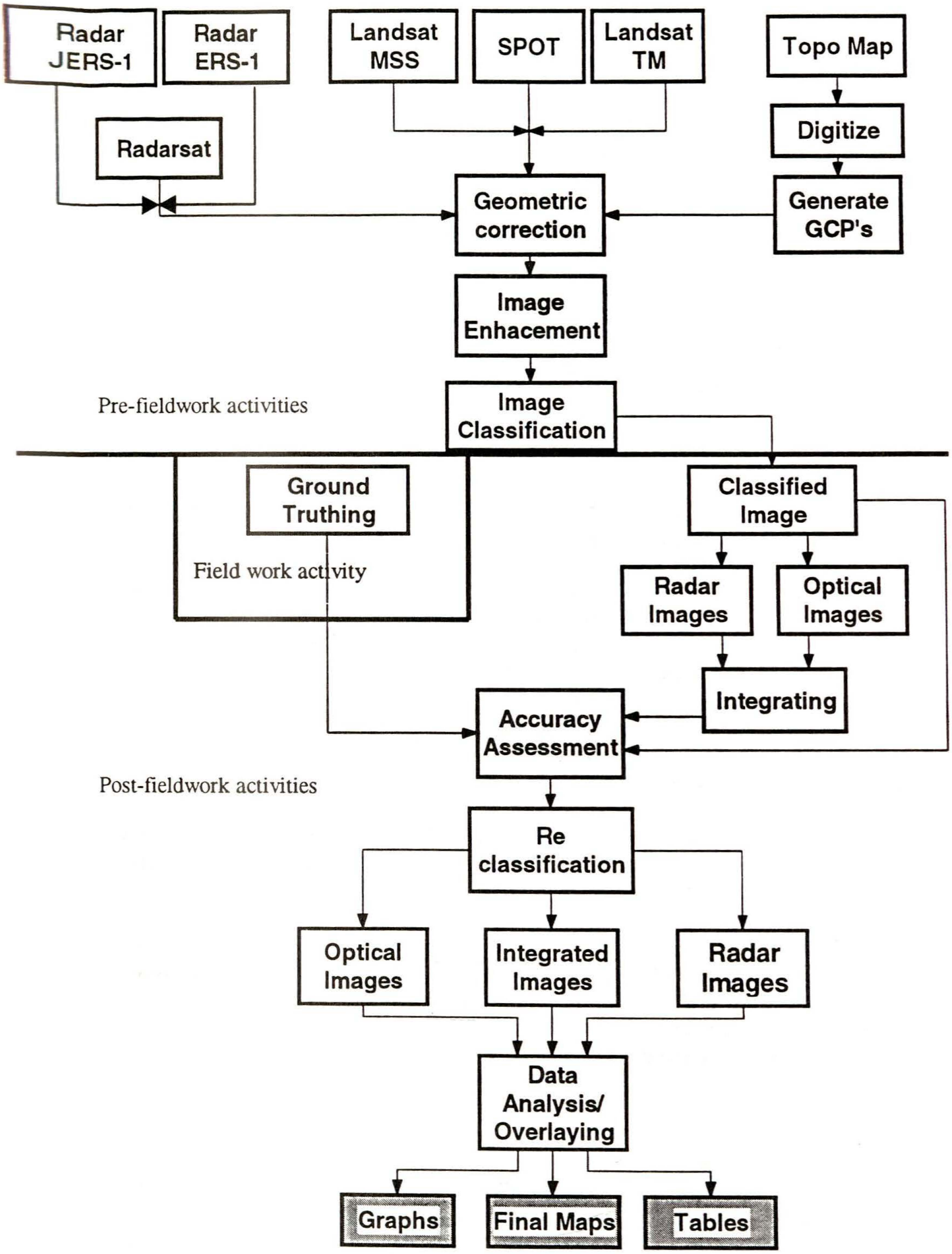

Radar JERS-1
Radar ERS-1
Radarsat
Landsat MSS
SPOT
Landsat TM
Topo Map
Digitize
Generate GCP's
Geometric correction
Image Enhacement
Pre-fieldwork activities
Image Classification
Ground Truthing
Field work activity
Classified Image
Radar Images
Optical Images
Integrating
Accuracy Assessment
Post-fieldwork activities
Re classification
Optical Images
Integrated Images
Radar Images
Data Analysis/ Overlaying
Graphs
Final Maps
Tables

Figure 1.—*Methodology flowchart.*

Table 1.—*Classes detected in each image through supervised classification and visual interpretation*

Landsat MSS	SPOT	Landsat TM	ERS-1	JERS-1	Radarsat
Broad-leaved	Broad-leaved	Broad-leaved	—	—	—
Nypa	Nypa	Nypa	Nypa	Nypa	Nypa
Water	Water	Water	Water	Water	Water
Ponds	Dry pond	Fish pond	Fish pond	Fish pond	Fish pond
—	Orchard	Orchard	—	—	—
—	Mixed	Mixed	Mixed	Mixed	Mixed
Agriculture	Agriculture	Agriculture	—	—	—
—	N/A	Clear cut	Clear cut	Clear cut	Clear cut
—	N/A	Half cut	—	Half cut	Half cut
—	—	Swampy	—	—	—
—	—	—	Oil pipeline	Oil pipeline	Oil pipeline

RESULTS AND DISCUSSIONS

Table 1 summarizes the classes identified on each image using supervised classification
Three types of mangrove deforestation were found to occur in the study area:

1. deforestation caused by establishment of agriculture and/or orchard
2. deforestation caused by establishment of oil pipeline networks
3. deforestation caused by the establishment of shrimp ponds

Deforestation resulting from the establishment of agriculture crops or orchards can be detected by Landsat TM 1994 and SPOT_XS 1987. However, radar data (JERS-1, ERS-1, and Radarsat) cannot detect this type of deforestation. Mangrove deforestation caused by establishment of an oil pipeline network cannot be detected on any of the optical images. On average, the oil pipelines are around 15 m wide, and they are surrounded by water and swampy vegetation. The spectral and spatial resolutions therefore prevent them from being imaged on optical images. However, pipelines are visible on all the radar images because they behave as corner reflectors as a vertically standing object on the ground. Mangrove deforestation caused by establishment of shrimp ponds can be detected on all optical and radar images, although ponds under construction, in which only about half of Nypa palm have been cut, can be detected only on the Landsat TM, JERS-1, and Radarsat images. ERS image could detect ponds and pipelines because of its short wavelength, small incidence angle and it is VV polarization. Since JERS radar image collected with longer wavelength, HH polarization and medium incidence angle while Radarsat is image collected by the same short wavelength of ERS, although with HH polarization and a medium incidence angle, it is believed that incidence angle played the important role to detect ponds and pipelines. The SPOT_XS 1987 image does not cover any areas with fish ponds.

The accuracy of each classification was assessed by comparison with data collected at sample points on the ground and compiling error matrices. To determine accuracy assessment for the deforested area (agriculture and/or orchards, ponds, and pipe line), all the corrected number of pixels in these classes were added, divided by the total number of pixels (correct + incorrect) in these classes, and the result multiplied by 100.

Based on data collected at sample sites in the field, the classification accuracy of each image to detect deforested mangrove area was as follows:

- 76% for Landsat MSS 1982, with 5 classes
- 89% for SPOT_XS 1987, with 7 classes
- 88% for Landsat TM 1994, with 9 classes
- 83% for ERS 1996, with 6 classes
- 85% for JERS 1996, with 7 classes
- 84% for Radarsat 1997, with 7 classes

CONCLUSIONS

Results of this research show that it is possible to differentiate between mangrove forest and non-mangrove cover types with all optical types of remotely sensed data. Specifically, it was found that:

- all optical data were able to differentiate fishponds,
- Landsat MSS and Spot XS data were able to differentiate only one agriculture class,
- Landsat TM data were able to differentiate two agriculture classes, and
- none of the optical data were able to differentiate oil pipeline establishment.

Using radar data to detect deforestation type, it was found that:

- all radar data were able to differentiate fishponds and clearcut areas,
- all radar data were able to identify the establishment of oil pipelines (using both spatial and backscatter information),
- none of the radar data were able to differentiate any agriculture classes, and
- JERS-1 and Radarsat images were able to differentiate partly cut Nypa palm (fish ponds under construction).

Given the accuracy percentage and the number of classes that resulted from these classifications, it seems that Landsat TM, Spot XS, and all radar images, especially JERS-1 and Radarsat, all give reasonable results in detecting deforested areas. There were no significant differences between the accuracy of these five data sets. However, Landsat MSS shows a significantly lower accuracy. It is possible that if optical data are fused with radar data, they may even give better results. Further research is therefore required to investigate whether optical and radar data can complement each other in detecting deforested mangrove areas.

Special Purpose Inventories and Applications

Using Secondary Metabolites in the Monitoring of the Condition of Tree Stands Under Industrial Pollution

I.L. Fuksman

Abstract.—The aim of this paper is to determine the optimal physiological indicator in diagnosing the condition of tree stands under the stress of industrial pollution. Based on experimental results of the fumigation on pine seedlings with sulphur dioxide, acid rain treatment, and the effect of heavy metals on the seedlings, it is reasonable to use the secondary substances or the so-called stress metabolites for this purpose. The greatest changes under the stress of industrial pollution are in the content of essential oils in pine needles. The contents of essential oils were examined and compared in regions with different levels of industrial pollution. The results of this study permit us to conclude that the alpha-pinene content in pine needles is the optimal indicator for the early diagnosis of the condition of woody plants under the stress of industrial pollution.

Examining the physiological-biochemical makeup of the organs and tissues of forest plants is one way to diagnose early the damaging effects of industrial pollution.

This paper presents the results of experiments on the fumigation of pine seedlings with sulphur dioxide, artificial acid rain treatment, and the effect of heavy metals on the seedlings. It has been shown that pine responds to pollutants by changing the composition and content of secondary substances (essential oils, phenols, growth substances) - the so-called stress metabolites. It seems reasonable to use the changes in the content of essential oils as an indicator in the early diagnosis of the condition of woody plants (Fuksman *et al.* 1996, 1997a, 1997b).

Essential oils were compared in the needles taken from middle-aged pine stands growing in areas with various degrees of pollution. The examination was conducted in background monitoring stands ("Kivach" reserve, 60 km from Petrozavodsk), in local monitoring stands insignificantly polluted with sulphur dioxide (the impact zone of the Kostomuksha ore-dressing mill in the territory of Karelia and Finland), and in stands chronically heavily polluted with sulphur dioxide and heavy metals (the vicinity of the "Severonickel" industrial combine near Monchegorsk).

The most expressed response of pine to the action of pollutants is the changes in the composition of essential oils with a considerable increase in the relative share of the most volatile components, especially alpha-pinene (Fuksman 1998).

This fact was most vividly demonstrated in the study of pine stands near Monchegorsk. Chromatograms of essential oils in pine needles from the most heavily polluted sample areas contained primarily one peak, corresponding to alpha-pinene.

Essential oils are thus an optimal indicator in diagnosing the condition of the stands under the stress of industrial pollution. Their identification by gas-liquid chromatography is easy enough, does not require much time, and is characterized by high reproducibility. These are the criteria for choosing an indicator to diagnose the condition of a tree stand (Yarmishko 1997).

It is suggested that the results obtained in this study be used in developing a scale for evaluating of the condition of pines by alpha-pinene content in the needles. A portable chromatograph and the direct plant material chromatography technique without preliminary separation of essential oils (Stepanov and Dubovenko 1970) allow the tree stand condition to be evaluated on site.

ACKNOWLEDGMENTS

The author is grateful to Valery A. Isidorov, St. Petersburg University, Department of Analytical Chemistry, and Vsevolod V. Polevoi, St. Petersburg University, Department of Plant Physiology.

The research was supported by the Russian Foundation for Basic Research (N 98-04-48484).

Professor, Laboratory for Physiology and Cytology of Woody Plants.

LITERATURE CITED

Fuksman, I.L. 1998. a-Pinene content in pine needles as the optimal indicator of the condition of woody plants under the stress of industrial pollution. Proceedings All-Russian Conference and Visiting scientific Session "Anthropogenic influence on the North nature and its ecological consequences;" 1998 June 22-25; Apatiti: 199-200.

Fuksman, I.L.; Gabukova, V.V.; Ivonis, I. Yu.; Novitskaya, L.L.; Shulyakovskaya, T.A. 1996. Estimation of physiological and biochemical characters for diagnosis of damaging *Pinus sylvestris* by pollutants. Journal of Forestry. 1: 57-63.

Fuksman, I.L.; Novitskaya, L.L.; Ivonis, I.Yu; Kanyuchkova, G.K.; Chinenova, L.A. 1997a. Effect of acidic rain on seedlings of scotch-pine (*Pinus sylvestris*). Rusian Journal of Ecology. 1: 3-8.

Fuksman, I.L.; Poikolainen, Y.; Shreders, S.M.; Kanyuchkova, G.K.; Chinenova, L.A. 1997b. Physiological and biochemical indication of the state of scotch pine under the influence of industrial pollution. Russian Journal of Ecology. 3: 213-217.

Stepanov, E.V.; Dubovenko, M.V. 1970. Analysis of volatile organic substances by the direct plant material chromatography technique. Izvestia of Russian Academy of Science, Biological Sciences. 3(15): 152-158.

Yarmishko, V.T. 1997. Scots pine and aerial pollution in the european North. St. Petersburg: Research Instituie of Chemistry of St. Petersburg State University. 210 p.

Integration of Ecological Indices in the Multivariate Evaluation of an Urban Inventory of Street Trees

J. Grabinsky, A. Aldama, A. Chacalo, and H.J. Vázquez

Abstract.—Inventory data of Mexico City´s street trees were studied using classical statistical arboricultural and ecological statistical approaches. Multivariate techniques were applied to both. Results did not differ substantially and were complementary. It was possible to reduce inventory data and to group species, boroughs, blocks, and variables.

Urban areas are increasing at a fast pace. In developed countries they can cover even more than the rural share of a state´s surface (Endress 1990). The advantages of and desires for urban forested areas are well documented and even recommended. Several international organizations, including the United Nations and the Interamerican Development Bank (Nilsson *et al.* 1996, Sorensen 1996) have shown great interest in developing street trees, forested areas, and parks in cities. There have been big loans and expenditures for planting campaigns and maintenance, with public acceptance.

Mexico City, which has become one of the biggest urban areas in the world, invests many resources each year in its trees, public and private. However, few and not very adequate studies have preceded or influenced the planting campaigns and maintenance operations. From 1993 to 1994, an inventory by sampling of Mexico City´s street trees was conducted, and the results were presented to city authorities and to the arboricultural scientific community.

Inventories by sampling should have statistical validity to infer characteristics about populations. To evaluate and unify concepts, an adequate set of descriptors must be constructed and these must have statistical validity to infer characteristics of the whole forest. The goal of this article is to present results with this aim, integrating the points of view of urban arborists and natural ecologists.

URBAN AND NATURAL FOREST INVENTORIES

It is not common to use ecological statistical modeling techniques in urban forest inventories, but the use of statistical indices in natural forests and ecology is well established (Ludwig and Reynolds 1988). Some attempts to translate these ideas and methodologies to the more complex urban settings have been made; for example, the concepts linked with "sustainable forest" (Clark *et al.* 1997). Multivariate techniques have been used to describe and to classify urban areas (Moll 1989, Sanders 1984).

Fewer published papers exist on the dynamics of urban forests or "street tree forests." The human side of this might be a deterrent on the usual natural diffusion processes and on the self-regulatory characteristics of the natural systems (Clark *et al.* 1997, Richards 1993).

Many aspects of the possible "optimal urban forest" have not been adequately identified and even less well managed; this is not surprising given, among other factors, the "short tenure of the administrators" (Richards 1993).

In the present state of the art in urban arboriculture, these formal mathematical and statistical approaches seem very difficult to follow. Nonetheless, some studies have been conducted to define guidelines to evaluate and manage urban systems (Richards 1993). Such guidelines may come from the adoption of a robust and very well chosen set of indices to identify decisive properties of the urban trees. Some of these characteristics are density, age distribution, species diversity, quality of planting sites (studied from the economical, geographical, biological, and edaphological points of view) and sanitary conditions. As mentioned before, some attempts have been made in urban arboriculture to evaluate these characteristics quantitatively, but the results have not been generally approved.

In natural ecology, the experience is much more extensive. Different indices exist to evaluate some properties such as *spatial distribution, diversity,* and *interspecific association* (Ludwig and Reynolds 1988):

- **Spatial distribution** is evaluated using the Index of dispersion (**ID** defined as sample variance over sample mean), **Green´s** Index, and the relation between the

---

Professor, Departamento de Ciencias Básicas; Professor, Departamento de Sistemas; Professor, Departamento de Energía; Professor, Departamento de Sistemas, respectively, Universidad Autónoma Metropolitana, Ave. San Pablo 180, Col. Reynosa Tamaulipas, 02200 Mexico D.F. Mexico.

observed species histogram and typical species distributions.

- **Species diversity is assessed in terms of** two distinct components: (1) abundance and (2) evenness. Abundance, number of species, is evaluated by indices such as **N0** the number of all species in the sample, **N1** related to the number of "abundant" species in the sample, **N2** related to the number of "very abundant" species. For evenness, different indices have been proposed, one of the most useful is the modified Hill´s ratio: **E5** = (**(N2-1/N1-1)**; (Ludwig and Reynolds 1988).

- **Interspecific association**, "how frequently" two species are found in the same location, is measured with the Jacard index, based on presence-absence matrices per block.

RESULTS OF MEXICO CITY´S STREET TREES INVENTORY

The inventory was done following accepted practices in urban ecology. Sixty-two variables and 1,260 trees were studied. Some of the main variables were height, diameter at a certain height, species, location, structure, wounds, interferences, dendrological characteristics, sanitary conditions, soil compaction, and sidewalk width (Chacalo *et al.* 1994).

Univariate and Bivariate Study

Broad main univariate and bivariate results were (Chacalo *et al.* 1994, 1996):

- Only eight species (dominant species described in table 2) had more than 5 percent of the individuals in the sample. In some boroughs two or three species accounted for the vast majority of the trees present in them.
- General Condition of the tree and Site Evaluation were significantly associated by borough, by blocks, by species, and in the whole sample as well.
- Plenty of damages and injuries were present in the trees. Vandalism was widespread.
- An average of 36.4 trees per block was calculated for the 866 blocks sampled.
- Maintenance was unsatisfactory, pruning was inadequate; earth and dead-tree removals were needed; too many interferences such as electric and telephone lines or other trees were present.
- Spatial distribution showed strong differences between boroughs in species and in number of trees in streets.
- Variety (number of species needed to account for 80 percent of the total number of individuals) in the boroughs ranged from 4 to 13.

Ecological Indices

An ecological evaluation of the sample trees in the Mexico City´s urban forest using the ecological indices presented before gives the following results:

- **Spatial distribution.** The eight most dominant species are spatially clumped by borough and block.
- **ID** is greater than 1 for boroughs (ranging from 2.18 for Bluegum to 6.82 for Cedar) and close to 2 for blocks. The observed species histogram has a good fit to a **negative binomial distribution**, a probability distribution model commonly observed when a population is clumped. **Green´s index** has numbers close to 0, meaning low clumpiness. This result is somehow inconsistent with **ID** and the observed species histogram. These spatial distribution results might mean weak overall (city) planning but strong local (borough) planning—not a big intervention of central or of individual planting decisions.

- **Diversity.** Ranges for the abundance values are **N0** (32 –192), **N1** (5.46-16.51), **N2** (5.12-13.63); range for the evenness index **E5** is (0.59 –1.11). Correlations among indices are in table 1.

The quantities obtained for the diversity indices and the evenness index are not very different from some

Table 1.—*Correlation table among indices related to diversity at borough level*

	N0	**N1**	**N2**	**Variety**	**E5**
N0	1.0				
N1	0.8452	1.0			
N2	0.8050	0.9505	1.0		
Variety	0.8417	0.9836	0.9305	1.0	
E5	-0.0086	0.0995	0.3817	0.0898	1.0

Table 2.—*Views obtained for the multivariate study*

View	**Individuals**	**Variables**
Tree	1,260	62
Species	more than 50	8 (for abundant species)
Dominant species[1]	CLR, ECL, CSR, FRS, TRN, JCR, CDR, OLM.	8
Borough	16 (official subdivisons)	6
Block	229	3

[1] Coral tree (CLR), bluegum (ECL), Australian pine (CSR), ash (FRS), privet (TRN), Brazilian rosewood (JCR), cedar (CDR), Elm (OLM).

mentioned for natural systems (Ludwig and Reynolds 1988).

- **Interspecific association.** Some slight associations between species exist: (bluegum and cedar), (bluegum and Australian pine), and (cedar and Australian pine). These were ratified with a multivariate study of the presence-absence matrices per block. Since trees in urban areas are not free to "choose" their habitats the low level of these associations is not surprising, taken in pairs or taken together.

However, this study did not make full use of the possibilities opened by the huge database, more than 75,000 entries. So, a full multivariate analysis was pursued constructing new variables and integrating ecological indices. ***Among the main objectives of this study were: to reduce and select a number of significant variables, to obtain a multidimensional view, and to identify groups of variables, species, boroughs, and blocks.*** For this, the database was studied under three different points of view: the tree itself, the species, and the site (borough or/and block).

Multivariate Study

A first multivariate study, using **M**ultiple **C**orrespondence **A**nalyses (MCA), was done for the 1,260 trees and for different sets of variables. Some of the main results were:

> No reduction in the number of included variables in the sampling could be achieved. That is, the 62 measured or observed characteristics of the tree and the site in which it was located, could not be grouped into a smaller set of clusters of variables. This may confirm that there were no conceptual redundancies, and that no variable could be "inferred" from other(s).
>
> The two constructed indices General Condition and Site Evaluation were consistent with its constituent variables and correlated for all the views (block, borough, tree, species).

Concerning the other views (**8** Dominant Species, **16** Boroughs, and **229** Blocks), variables and indices constructed were obtained from the 62 original variables. Our results yielded a reduction in dimensionality (high percentage of variance explained by a reduced number of variables) for these three statistical views; using **P**rincipal **C**omponent **A**nalyses (PCA), it was possible to concentrate an important percentage of variance into two axes.

Principal **C**omponent **A**nalyses, **C**luster **A**nalyses, and the Spearman rank test confirmed the following results:

> By **SPECIES**, four variables were initially used: General Condition, Site Evaluation, Socioeconomic Level, and Age Distribution. Just the first two variables formed a group.
>
> Three groups of species were detected (fig. 1a). **Group 1**, which has the worst General Condition, is located in bad sites (physically and

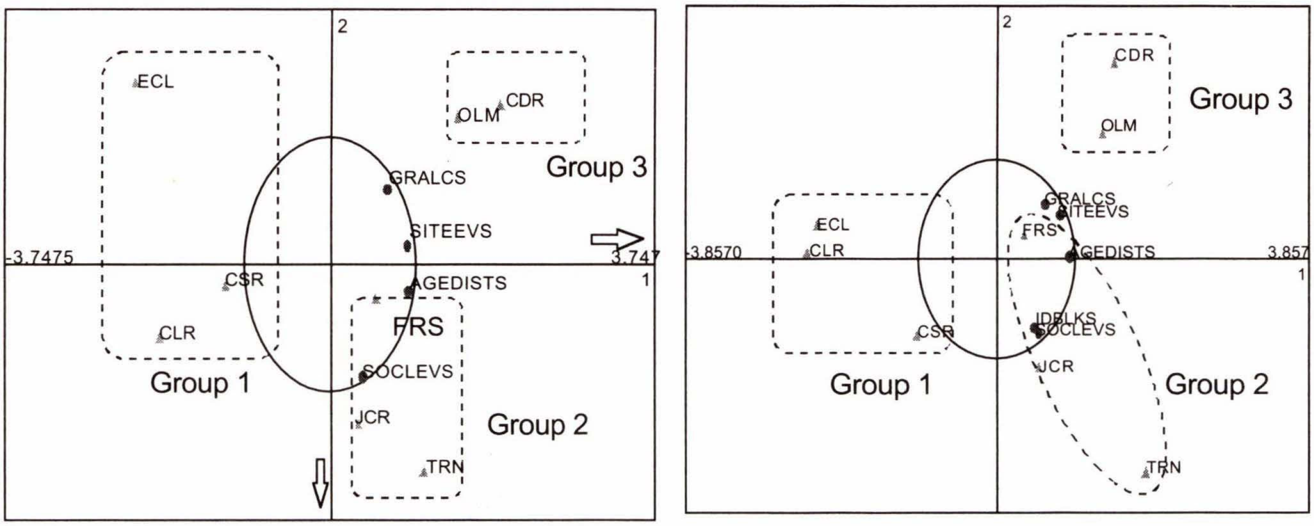


Figure 1a.

Figure 1b

Species: Coral tree (CLR), bluegum (ECL), Australian pine (CSR), ash (FRS), privet (TRN), Brazilian rosewood (JCR), cedar (CDR), elm (OLM).

Figure 1.—*Principal component analysis by species.*

economically) and is far from the Age Distribution used as reference. **Group 2** is located at the best Socioeconomic Levels. **Group 3** has the best General Condition and is located in the better sites. Both Groups 2 and 3 have good Age Distributions.

The axis, formed by General Condition, Site Evaluation and Age Distribution, was interpreted as a measure of **ecological quality**; the second one was just related with Socioeconomic Level.

The inclusion of ecological indices, Spatial pattern **ID** and **Green´s**, did not produce, at first glance, substantial changes. The same three groups were detected. In the first two PCA axes (70.41 percent of total variance), these two indices appeared together with the variable Socioeconomic Level (fig. 1b). This was not confirmed clearly by cluster analyses; for this reason, it seemed important to consider PCA´s third axis.

On the plane formed by axes 1 and 3 (66.15 percent of total variance), just two groups appeared: **Group 1**: ash (FRS), privet (TRN), Brazilian rosewood (JCR), cedar (CDR), and elm (OLM); **Group 2**: coral tree (CLR), bluegum (ECL), and Australian pine (CSR). The **ID** index appears close to General Condition and not far from Site Evaluation; when both groups of species are superimposed, **ID** appears close to **Group 1**. *This means that species in Group 1 are located in better sites, at better Socioeconomic Levels; have Good General Condition and bad Age Distribution; and are more clumped.*

By **BOROUGHS,** initially six variables were used: Variety (number of species in 80 percent of the individuals), General Condition, Site Evaluation, Socioeconomic Level, Tree Density per Block, and Age Distribution.

PCA results for the first two axes are (fig. 2a):

> **Set 1**: view General Condition-Site Evaluation as already observed on the tree view study.
> **Set 2**: Socioeconomic Level-Tree Density per Block—more trees are found on average in richer neighborhoods.
> **Set 3**: Variety-Age Distribution—greater Variety corresponds to better Age Distribution.

General Condition and Site Evaluation, **Set 1**, appears related with the first axis, and Variety

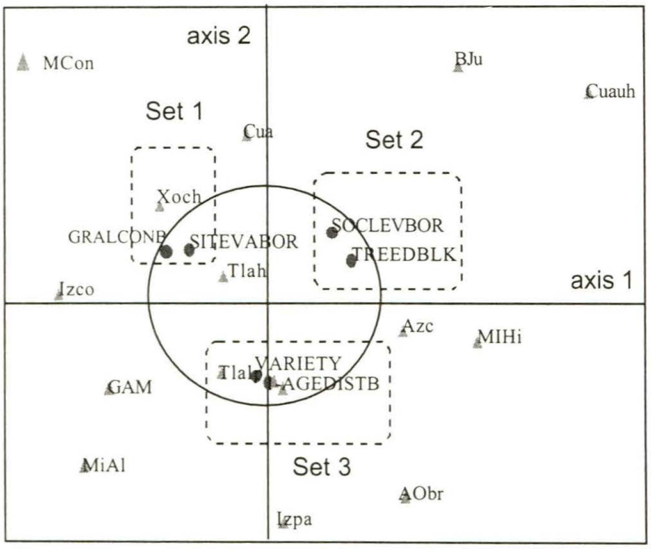


Figure 2a.

PCA (16 boroughs/6 arboricultural variables)

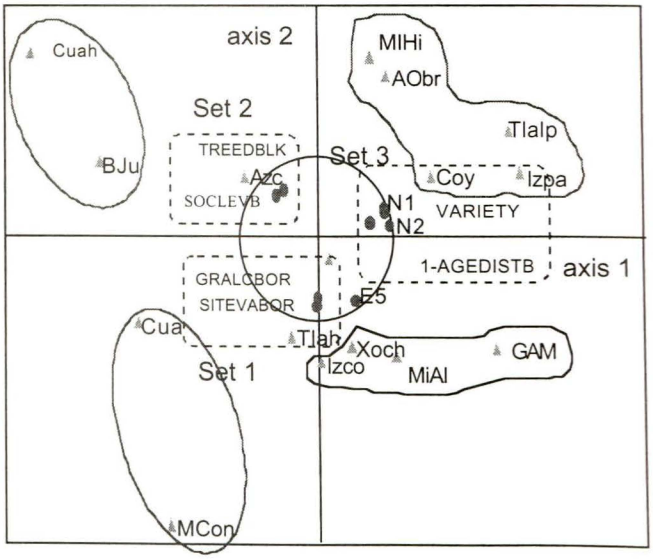


Figure 2b.

PCA (16 boroughs/ 6 arboricultural and 3 ecological variables)

Figure 2.—*Principal component analysis by boroughs.*

and Age Distribution, **Set 2**, appears related with the second axis. **Set 3** appears related to axis 1 and 2. Healthy boroughs characterized by good sites do not necessarily have good Socioeconomic Levels or high Tree Density.

The first axis was taken as the "***matching quality***" of specific sites and trees, while the second axis was roughly defined as an indicator of ***biological*** and ***temporal diversity*** of the forest.

PCA results (axes 1 and 2 representing 68.69 percent of total variance), with the inclusion of the abundance (**N1, N2**) and evenness (**E5**) indices to the initial six variables, gives the following (fig. 2b):

- The relative positions of the six initial variables did not change: **Set 1**: General Condition-Site Evaluation. **Set 2**: Socioeconomic Level-Tree Density per Block and **Set 3**: Variety-Age Distribution.
- Indices **N1** and **N2** join the **Set 3**, which is not surprising, because they are also measures of Variety.

The evenness index, **E5**, at first glance, joins **Set 1**. However, cluster analysis associates **E5** and Age Distribution. On the plane formed by axes 1 and 3 (14.35 percent of total variance), **E5** and Age Distribution appear together again. So, **E5** seems to be related with both General Condition and Age Distribution.

Evenness is better when matching quality between trees and sites increases and when abundance increases. When the 16 boroughs are superimposed with the variables on axes 1 and 2, the configuration of the boroughs does not change significantly; however, the inclusion of Evenness reduced distances inside the different groups, so they are more closely associated.

When the 16 boroughs are seen in clusters, some significant geographic patterns are detected, having to do with their distance to the older downtown areas of the city, closeness to the mountains and ravines, on the environs of the remaining lakes and forests (fig. 3c).

By **BLOCKS**, five characteristics—General Condition, Site Evaluation, Socioeconomic Level, Block Variety, and Age Distribution—are considered. For the 229 blocks studied, the two global indices, General Condition and Site Evaluation, are seen to be grouped on the two first PCA axis (58 percent of total variance). This meaning that two axes can explain 58 percent of the information represented by the five original variables.

Block Variety and Age Distribution also appear to be grouped. Socioeconomic Level does not seem to play a role in the constitution of the first two axes. However, on axes 1 and 3 (54 percent of total variance), the 229 blocks split in two groups as a function of Socioeconomic Level.

Of the 229 blocks, 166 are in the lowest socioeconomic level and 63 in the highest. For the variables General Condition, Site Evaluation, and Block Variety, **five** groups are observed. This corresponds with the number of species found on each of the 229 blocks.

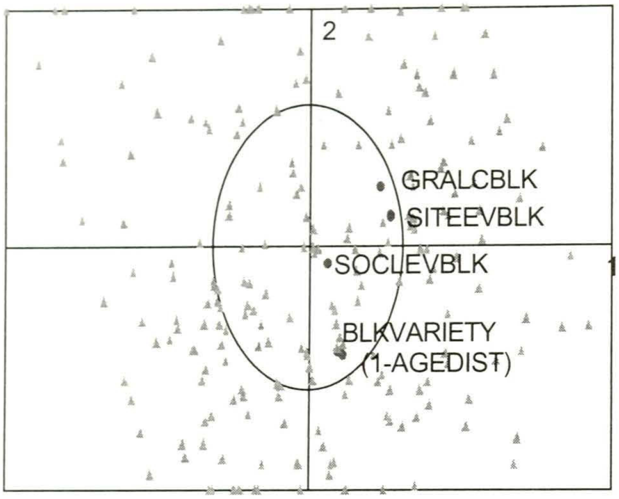
CONCLUSIONS

Techniques such as satellite photos, geographical information systems, and rapid sampling (Jaenson *et al.* 1992 mentioned in Richards 1983) have been used recently for characterizing urban trees. Nonetheless, we believe that this has to be complemented with a more detailed description of the urban forest, if one aspires to understand the dynamics and evaluate the actions that have been or should be taken. Such a description might include environmental, neighborhood, and individual tree information of biological, physical, edaphological, economical, geographical, and historical types. Street tree inventories and their analysis using multivariate techniques constitute an important source of information to describe the structure of the forest and how it is affected and how it should be managed to improve it.

Both points of view, urban and natural, allow a more systematic understanding of the multiple factors involved, their role, their interactions, and possible cause-effect relations. All these factors constitute a basis for developing and even defining an optimal forest for a given city. Multivariate techniques have proven to be useful in providing a solid basis for comparing and identifying criteria for management purposes.

The ecological indices in this urban database did not produce very different results from those obtained in the study of natural systems: negative binomial distribution of species and high correlation of the diversity indices.

The inclusion of the ecological indices corroborated previous multivariate results and validated their findings (Vázquez 1997). The results of both methods were complementary.



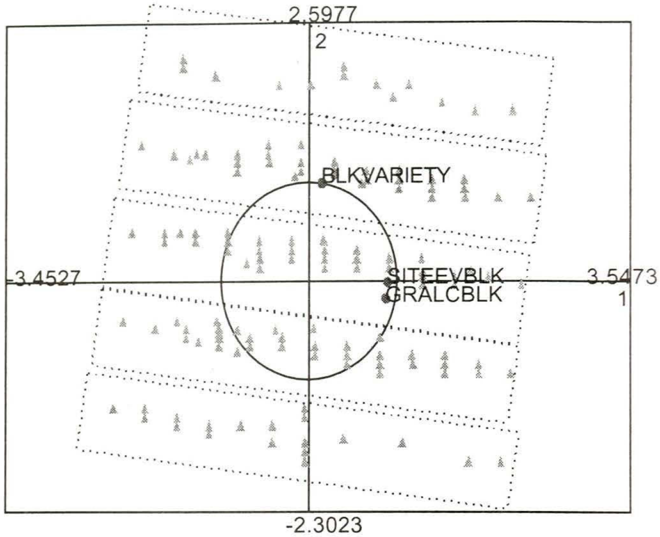


Figure 3a
PCA (8 blocks/ 5 arboricultural variables)

Figure 3 b
PCA (8 blocks/ 3 arboricultural).

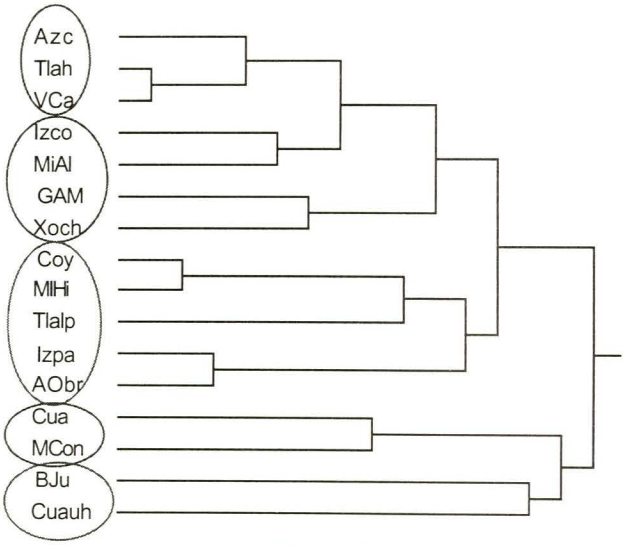


Figure 3c.
Cluster Analysis (16 boroughs/6 arboricultural and 3 ecological variables

16 official boroughs: AObr, MiHi, Cuauh, Bju, Azc, Izpa, MiAl, GAM, Tlalp, Tlah, Izco, Xoch, Cua, MCon, Coy, VC.

Figure 3.—*Principal component analysis by blocks.*

ACKNOWLEDGMENTS

The authors thank Dr. Alain Hartmann and Dr. Sophie Cliquet for their valuable comments.

The following people reviewed this manuscript: Alain Hartmann, National Research Aricultural Institut Dijon, CMSE, Labo.de Microbiologie des Sols, 17 rue Sully, 21000 Dijon, France, and Sophie Cliquet, IUP IIA, Université de Bretagne Occidentale, Creach Gwenn, 29000 Quimper, France.

LITERATURE CITED

Chacalo, A.; Aldama, A.; Grabinsky, J. 1994. Street tree inventory in Mexico City. Journal of Arboriculture. 20(4): 222-226.

Chacalo, A.; Grabinsky, J.; Aldama, A. 1996. Inventario del Arbolado de Alineación de la Ciudad de México. Ciencia Forestal. 21(79), México D.F., Mexico.

Clark, R.J.; Matheny, N.P.; Cross, G.; Wake, V. 1997. A model of urban forest sustainability. Journal of Arboriculture. 23(1): 17-30.

Endress, A.G. 1990. The importance of diversity in selecting trees for urban areas. Journal of Arboriculture. 16(6): 143-147.

Harris, R.W. 1992. Arboriculture: integrated management of landscape trees, shrubs and vines. 2d ed. New Jersey: Prentice Hall, Inc.

Jaenson, R.; Bassuk, N.; Schwager, S.; Headley, D. 1992. A statistical method for the accurate and rapid sampling of urban street tree populations. Journal of Arboriculture. 17: 185-191.

Lebart, L.; Morineau, A.; Warwick, K. 1984. Multivariate descriptive statistical analysis. John Wiley.

Ludwig, J.A.; Reynolds, J.F. 1988. Statistical ecology. Wiley.

Moll, G. 1989. Improving the health of the urban forest. In: Moll, G.; Ebenreck, S., eds. Shading our cities. A resource guide for urban and community forests. Washington: Island Press: 119-103.

Nilsson, J.; Randrup, T.; Tvedt, T. 1996. Technological aspects of urban greening. Draft presented at the International seminar on urban greening in Latin America and the Caribbean. Mexico City. DDF, BID, Gobierno del Estado de México. México.

Sorensen, M. 1996. Introducción a la Creación de Areas Verdes Urbanas. No. ENV96-103. BID, 71 p. Washington, DC.

Richards, N.A. 1983. Diversity and stability in street tree population. Urban Ecology. 7: 159-171.

Richards, N.A.1993. Reasonable guidelines for street tree diversity. Journal of Arboriculture. 19(6): 344-349.

Sanders, R. 1984. Some determinations of urban forest structure. Urban Ecology. 8(1/2): 13-27.

Vázquez, H.; Grabinsky, J.; Aldama, A.; Chacalo, A. 1997. Exploratory multivariate analyses of Mexico City´s tree inventory data. SPRUCE IV Enschede, Holland September, 1997.

Modeling White-tailed Deer Activity Patterns Across Forested Landscapes

Linda S. Gribko, Michael E. Hohn, and William M. Ford

Abstract.—White-tailed deer (*Odocoileus virginianus*) herbivory has been identified as a major impediment to the survival and growth of forest regeneration in the northeastern United States. As a supplement to direct control of deer densities through hunting, it may be possible for land managers to manipulate habitat and browsing pressure through carefully planned timber harvest. We are developing methods to relate deer habitat use patterns to regeneration condition and complexity across large landscapes. The preliminary research presented here involved development of methodology to efficiently and effectively model deer habitat use patterns across forested landscapes using fecal pellet groups as an activity index.

Work was conducted in summer 1997 on the 3,078-ha West Virginia University Forest (WVUF) in north-central West Virginia and the 3,413-ha Westvaco Wildlife and Ecosystem Research Forest (WERF) in the south-central portion of the state. Fecal pellet group counts were conducted on geolocated 1.72-m radius circular plots at an intensity of approximately 1 plot per 2.4 ha. We used variography to investigate spatial dependence in the data. Deposition patterns were modeled using geographic information systems (GIS) technology and a spatial statistics technique known as two-dimensional ordinary point kriging. Variography revealed spatial contagion in the WVUF data that could be accurately modeled using this methodology. The resulting interpolated probability map is of high potential value in the long-term monitoring of deer activity patterns across this forested landscape. Results on the WERF indicated that sampling intensity was too coarse to allow modeling of strong localized dependence in the data.

Excessive white-tailed deer (*Odocoileus virginianus*) herbivory, or browsing, has been identified as a major impediment to the survival and growth of tree seedlings and herbaceous plants in the northeastern United States (Shafer *et al.* 1961, Tierson *et al.* 1966, Jordan 1967, Alverson *et al.* 1988, Tilghman 1989, Trumbull *et al.* 1989). Browsing can affect forest regeneration by reducing seedling numbers, reducing seedling height, altering species composition, delaying stand establishment, or causing complete regeneration failure (Redding 1987). Of particular concern to forest managers are conversions of woody understories to ferns and grasses (Marquis 1974, Horsely and Marquis 1983) and the elimination of highly valued commercial tree species such as northern red oak (*Quercus rubra*) from the pool of large advance regeneration under mature forest canopies (Marquis *et al.* 1976). Severely impacted forest ecosystems are devoid of most understory plants that are palatable to deer and may exhibit an overall reduction in animal diversity (deCalesta 1994).

Deer herbivory research conducted to date suggests that deer population densities in many forested landscapes should be reduced (Behrend *et al.* 1970, Marquis 1981, Storm *et al.* 1989, Bowersox *et al.* 1993, McCormick *et al.* 1993). However, the public demand for deer hunting opportunity often outweighs concerns about browsing impacts; state wildlife agencies are consequently reluctant to lower deer densities to suggested levels (Sheffer 1987).

Rather than attempting to control deer densities directly through harvest, it may be possible to manage forested landscapes to reduce browsing pressure and regeneration damage. The manipulation of the spatial distribution of clearcuts has been suggested as one means of accomplishing this objective (Ford *et al.* 1994). Deer extensively forage in recent clearcuts during spring and summer when succulent leaves and new growth are available (Wentworth *et al.* 1990, Ford *et al.* 1993). In the central and southern Appalachians, the availability of clearcuts has been found to increase carrying capacity of the surrounding forest and reduce browsing pressure on forested understories during the summer (Johnson *et al.* 1995). Careful planning of the intensity, timing, and location of timber harvest areas may allow managers to draw deer away from forested understories while maintaining the population at a sufficient density to provide adequate hunting opportunity.

Assistant Professor of Forest Management, West Virginia University, Morgantown, WV, USA; Senior Research Geologist, West Virginia Geological and Economic Survey, Morgantown, WV, USA; Wildlife Biologist, Westvaco Corporation, Rupert, WV, USA, respectively.

Currently, a lack of deer herbivory research conducted at the landscape level constrains the development of forest management recommendations. Most studies have considered localized, or stand-level, effects of deer browsing. Investigators have considered the impacts of deer in contiguous closed-canopy forests (Marquis 1981), in small isolated woodlots (Storm *et al.* 1989, Bowersox *et al.* 1993), in recently clearcut areas (Marquis and Grisez 1978), or after specific stand treatments such as thinnings (McCormick *et al.* 1993). Typically, such research has involved comparisons of areas with varying densities of deer or the use of fencing and barriers to manipulate deer impacts. Work at larger spatial scales (500- to 1,000-ac blocks) was recently initiated in Pennsylvania (Stout *et al.* 1995). However, the highly fragmented, severely browsed forests of Pennsylvania may not be comparable to the more continuous, less intensively browsed forests found elsewhere in the Appalachian region.

In 1997, we initiated a study designed to relate deer habitat use patterns to woody regeneration condition and complexity across landscapes dominated by relatively continuous closed-canopy second-growth hardwood forest. This paper reports the results of the first phase of study in which we developed a method of quantifying landscape-level deer habitat use patterns using fecal pellet group counts as an activity index. Generally, pellet groups are counted on either rectangular belt transects (Bennett *et al.* 1940, Robinette *et al.* 1958, Fuller 1991) or circular plots of various dimensions (Eberhardt and Van Etten 1956, Robinette *et al.* 1958, Van Etten and Bennett 1965). Counts of fecal pellet groups are widely used to census deer populations and to determine habitat use (Neff 1968). Average counts within management units or habitat types are compared as relative indices of deer abundance or are used with defecation rate to estimate population densities. Bennett *et al.* (1940) found that deer defecate close to feeding areas, indicating that high densities of fecal pellets may be associated with high levels of herbivory.

Traditionally, spatial patterns of pellet group deposition are not considered. However, if the spatial dependency among fecal pellet counts made at a large number of discreet points throughout a forested landscape is strong enough to be modeled, the relationship could be used to estimate pellet count densities at unsampled locations. A map, or data layer, of predetermined spatial resolution would result. The field of geology offers techniques, termed geostatistics, that can be used to quantify the inherent spatial dependencies in data and use them to create interpolated data coverages. Although developed to model petroleum and mineral reserves, geostatistics have also been used in the modeling of ecological data (Robertson 1987, Rossi *et al.* 1992, Pelletier and Parma 1994, Villard and Maurer 1996). One of these techniques, *kriging*, has been applied outside of the geological sciences to model insect outbreaks (Kemp *et al.* 1989, Liebhold *et al.* 1991, Hohn *et al.* 1993, Gribko *et al.* 1995), forest biomass and nutrient cycles (Pauley *et al.* 1996), and old-growth forest characteristics (Biondi *et al.* 1994).

The purpose of this study was to determine if fecal pellet group counts made at discrete points could be used to model deer activity patterns across a forested landscape. Specific objectives included: (1) to quantify the spatial dependence inherent in deer fecal group deposition, and (2) to determine the suitability of geostatistical techniques, specifically two-dimensional ordinary point kriging, in mapping white-tailed deer use of forested landscapes.

METHODS

Study Areas

The study was conducted on two sites: the 3,078-ha West Virginia University Forest (WVUF) in Monongalia and Preston Counties, WV, and the 3,413-ha Westvaco Wildlife and Ecosystem Research Forest (WERF) in Randolph County, WV. The WVUF is located on the westernmost anticline of the Allegheny Mountains. Elevations range from 318 to 796 m. The tract is covered by closed-canopy 70- to 80-year-old hardwood forest; no more than 200 ha have been impacted by timber harvest or major canopy disturbance in the past 20 years. Four forest types as classified by SAF (Eyre 1980) have been identified on the WVUF: yellow-poplar (*Liriodendron tulipifera*)-white oak (*Quercus alba*)-northern red oak (*Quercus rubra*); white oak-black oak (*Quercus velutina*)-northern red oak; chestnut oak (*Quercus prinus*); and yellow-poplar (*Liriodendron tulipifera*). The two types containing yellow-poplar components are found in protected coves, on north and east aspects, and at shaded midslope positions. The oak-dominated types are found on the drier, less protected sites; the chestnut oak type is constrained primarily to ridgetops and upper slope positions.

Elevations on the WERF range from 699 to 1,176 m. The topography is dominated by a series of ridges oriented northeast to southwest. Ninety-seven percent of the forested area is made up of 60- to 70-year-old stands of mature hardwoods. However, the majority of the mature stands have been partially harvested at least once in the past decade, and canopy cover is not continuous. The WERF includes three forest types in addition to 140 ha of open or non-forested land. Ninety percent of the forest cover is classified as the sugar maple (*Acer saccharum*)-beech (*Fagus grandifolia*)-yellow birch (*Betula allegheniensis*) SAF type; associated species include white ash (*Fraxinus americana)*, American basswood (*Tilia americana*), black cherry (*Prunus serrotina*), yellow-poplar, and northern red oak. The yellow-poplar—white oak—northern red oak type is found on 195 ha of protected coves. The remaining 21 ha are classified as the white oak SAF type; associated species include chestnut oak, scarlet oak (*Querucs coccinea*), black oak, and hickory (*Carya* spp.).

Field Methods

Data were collected in summer 1997. Sample points were established in an approximately square-grid pattern at an intensity of approximately 1 per 2.4 ha. In total, 1,400 points were located on the WVUF and 1,445 points were located on the WERF. The points were georeferenced using a handheld GPS unit and fixed base station that allowed differential correction of the satellite locations. Each point was the center of a 1.72-m-(9.29 m^2) radius circular plot on which fecal pellet surveys were conducted (Robinette *et al.* 1958, Van Etten and Bennett 1965). Pellet groups on each of the plots were counted once from June to July on the WVUF and from August to September on the WERF. All pellets were destroyed by crushing. The counts provided baseline data and were not assumed to represent deer activity during any specific season.

Data Analysis

Topographic Variables

We first had to examine the relationships between pellet group densities and possibly confounding variables related to topography. Digital elevation models (DEM's) were available for both experimental forests. The model for the WERF was developed by Westvaco personnel at a resolution of slightly over 15 m. The 30-m resolution USGS DEM was used to describe the topography of the WVUF. We calculated percent slope and aspect in degrees azimuth using the elevation data and the raster-based geographic information system (GIS), IDRISI (Citation). We then standardized the aspect data by subtracting 180 degrees and taking the absolute value of the difference, effectively lumping the data collected on approximately eastern and western aspects (intermediate site quality) while segregating data collected on approximately northern (highest site quality) and southern (lowest site quality) aspects. For each experimental forest, pellet group data were plotted against elevation, slope, and aspect, and relationships were examined.

Variography

Spatial dependence on each experimental forest was quantified with the variogram, a graph that illustrates the relationship between the distance separating pairs of data points (h) and half the average squared deviation of a regionalized variable ($\gamma(h)$). In this case, the variogram statistic at each given distance h represents half the average squared difference between paired fecal pellet group counts separated by that particular distance (Hohn 1988, Isaaks and Srivastava 1989, Liebhold *et al.* 1991, Rossi *et al.* 1992). The variogram statistic is defined as

$$\gamma(h)=\frac{1}{2n}\sum_{k=1}^{n_h}\left[z(x_k)-z(x_k+h)\right]^2$$

where n_h is the number of pairs of cells separated by a distance of h (expressed in meters in this study), $z(x_k)$ is the observed pellet group count at location x_k, and $z(x_k + h)$ is the observed count at a location h meters from x_k. In the absence of spatial dependence, the variogram is constant with distance h. In the presence of strong spatial dependence, the difference between $z(x_k)$ and $z(x_k + h)$ will be relatively small when h is small and will increase with separation distance. At some distance, the difference between counts fails to increase further and the variogram levels off. This distance is referred to as the *range* of the variogram. The value of $\gamma(h)$ at the range is called the *sill*. In general, one would expect the variogram to originate at the origin; however, variograms manifest a non-zero y-intercept when some component of the variability is non-spatial or on a smaller scale than sample spacing.

For each experimental forest, VARIOWIN version 2.2 (Pannatier 1996) was used to calculate the variogram statistic in 120-m lags with a 60-m tolerance to a maximum separation distance of 1,200 m. The first lag included pairs having a separation distance smaller than the tolerance; in other words, all pairs separated by less than 60 m. The few pairs in this lag were retained rather than disregarded. The relationship between pairs separated by more than 1,200 m was not considered. Surface plots of the variogram statistics calculated in the east-west direction versus those calculated in the north-south direction were examined for indications of directionality in the data (figs. 1-2). In the presence of strong directional trends, several individual models are required to accurately describe the spatial dependence in the data. In its absence, a single omnidirectional model is sufficient. In neither data set was there discernible directionality.

Omnidirectional variograms for each forest were plotted using VARIOWIN, and models were fit iteratively by eye (Hohn 1988). Single and nested linear, exponential, gaussian, and spherical model forms were tested for general fit to the shape of the variograms, and the models were fine-tuned by alternately adjusting the *sill* and the *range*. Special care was taken to fit the first few lags accurately, so the final models may or may not have exhibited the best overall goodness of fit. In both cases, the origin was forced through zero.

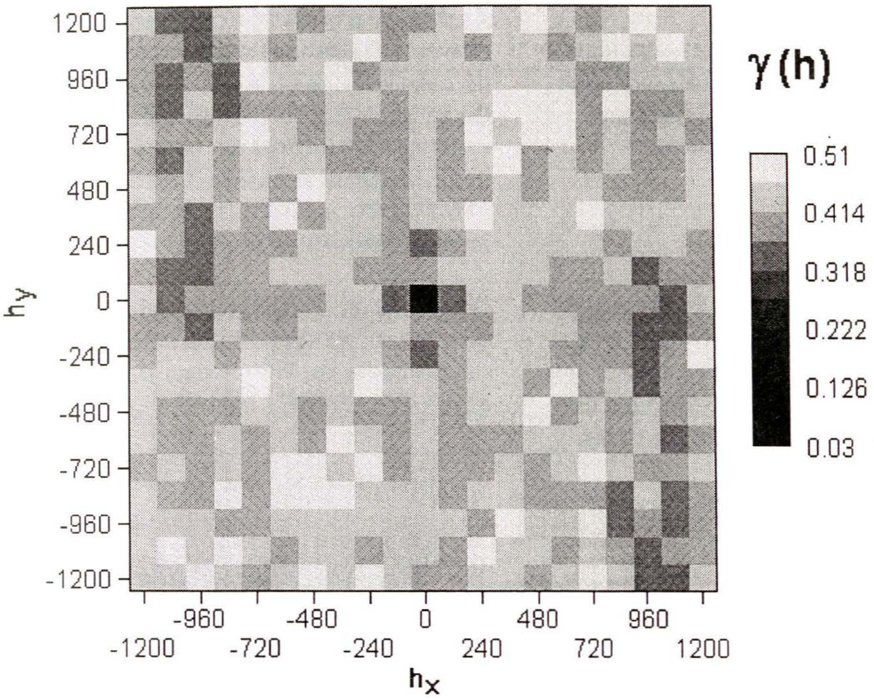


Figure 1.—*Variogram surface for the West Virginia University Forest (WVUF).*

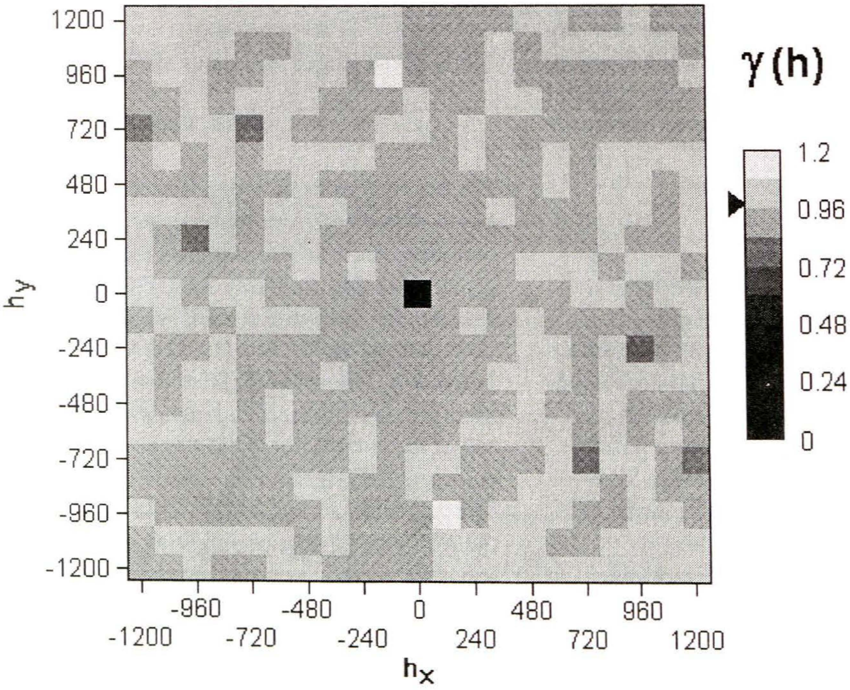


Figure 2.—*Variogram surface for the Westvaco Wildlife and Ecosystem Research Forest (WERF).*

Kriging

Results of the variogram analysis were used to calculate weights employed in the two-dimensional ordinary point kriging of the pellet count data. Kriged estimates are weighted averages of values at nearby locations

$$z^* = \sum_{j=0}^{n} w_j \bullet z_j$$

where z^* is the interpolated value being estimated, $z = [z_1, z_2, z_3, \ldots, z_n]$ is the vector of values at nearby locations, and $w = [w_1, w_2, w_3, \ldots, w_n]$ is the vector of corresponding weights to be used in averaging the values. Because the *kriging* procedure minimizes the variance of the errors, the weight matrix can be estimated as

$$w = C^{-1} \bullet D$$

where C is the $(n+1)$ by $(n+1)$ covariance matrix and all the z values from nearby samples and D is the $n+1$ vector of covariances of z values between the point being estimated and the nearby samples. The covariances can be computed directly from the variogram as

$$\mathrm{cov}(h) = c - \gamma(h)$$

where c is the variogram sill.

GSLIB version 2.0 was used to krig the data (Deutsch and Journel 1998). Kriged estimates were made at a 30-m resolution and were based on at least 2, but no more than 36, values collected within 500 m of each unsampled location. Estimates made near the boundaries of the experimental forests were necessarily based on fewer samples than those made in the interior.

RESULTS

There were no strong identifiable relationships between the topographic variables and pellet group counts on either of the experimental forests. Aspect may have some effect on the WERF as evidenced by somewhat depressed, but statistically insignificant, pellet group counts on the more southerly aspects. It appears that elevation possibly may be related to counts on the WVUF; however, high pellet group densities at elevations over 600 m were clustered on a portion of the forest that was heavily impacted by overstory mortality in 1990-1991. Higher counts in these areas were likely related to browse availability rather than elevation. Linear regressions through these data were all essentially horizontal with R^2 values less than 0.01. No attempt was made to transform the data.

The variogram surface plots revealed no directional dependence in the WVUF data (fig. 1). Weakly elevated dependence was suggested among pellet plots oriented in a northeast to northwest direction on the WERF (fig. 2). However, the trend was not strong enough to necessitate the calculation of directional variograms. The majority of the cells in the variogram surface had values of approximately 0.72-0.96; had the values been appreciably lower in the northeast-northwest direction (perhaps in the range of 0.24-0.48), a pair of directional variograms may have improved our ability to model the data.

Omnidirectional variograms and the final fitted models for both forests are shown in figures 3-4. The variogram calculated for the WVUF data was fit with the nested exponential model:

$$\gamma(h)=0.415\left[1-e^{\frac{-3|h|}{231}}\right]+0.015\left[1-e^{\frac{-3|h|}{156}}\right]$$

The omnidirectional variogram for the WERF was fit with the nested model:

$$\gamma(h)=0.75\left[1.5\frac{|h|}{92}-0.5\left(\frac{|h|}{92}\right)^3\right]+0.20\left[1-e^{\frac{-3|h|}{485.48}}\right]$$

if $|h| \leq 92$,

else,

$$\gamma(h)=0.75+0.20\left[1-e^{\frac{-3|h|}{485.48}}\right] .$$

The first structure in this model is spherical; the second is exponential.

Maps of the kriged estimates are displayed in figures 5-6.

DISCUSSION

The absence of both strong directional trends and strong associations with topographic variables simplifies the modeling process and suggests that differences in pellet group densities are likely related to differences in habitat quality. On both of the study sites, a single omnidirectional model can be used to describe the spatial contagion in the data. In addition, there is no apparent need to incorporate additional independent variables through the use of more complex geostatistical techniques such as cokriging or kriging with external drift (Goovaerts 1997, Deutsch and Journel 1998). This will allow us to monitor the response of deer populations to timber management activities across the study sites without the added complication of confounding variables.

Because the exact location and orientation of the sample plots were not critical in this initial exploratory study, we used temporary locations with the distance between plots paced, rather than measured. This facilitated more rapid data collection but also resulted in less uniformity in the sample design; some plots were installed in closer

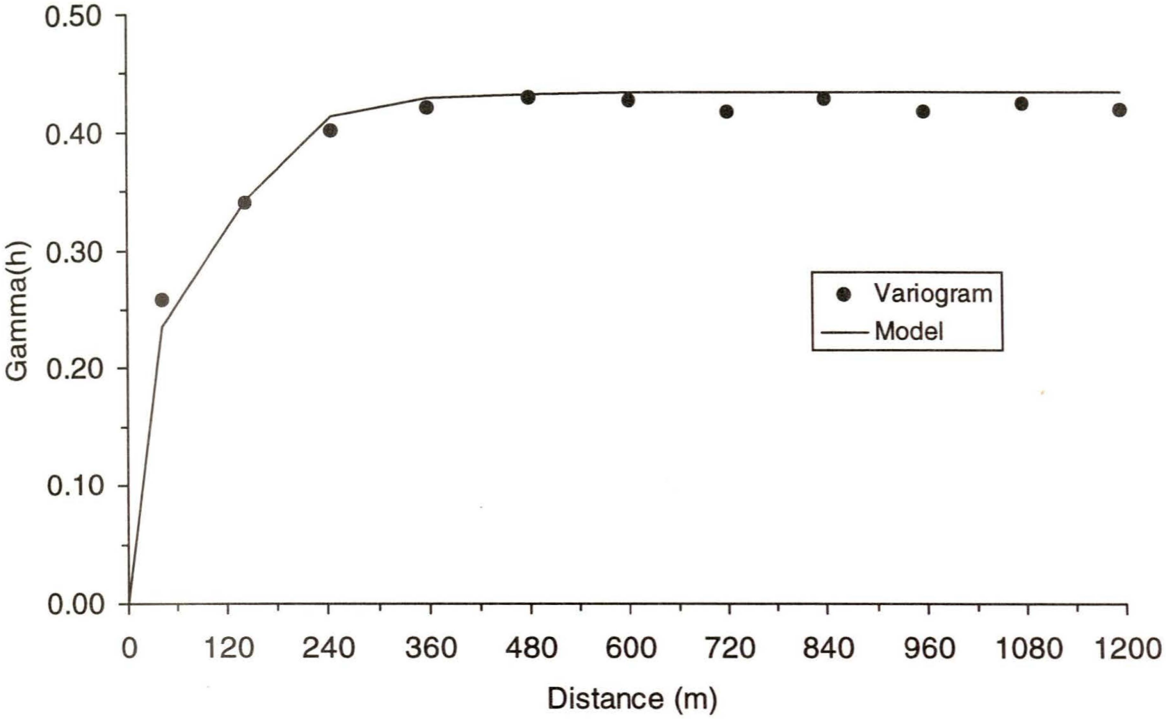


Figure 3.—*Variogram and fitted model for the WVUF.*

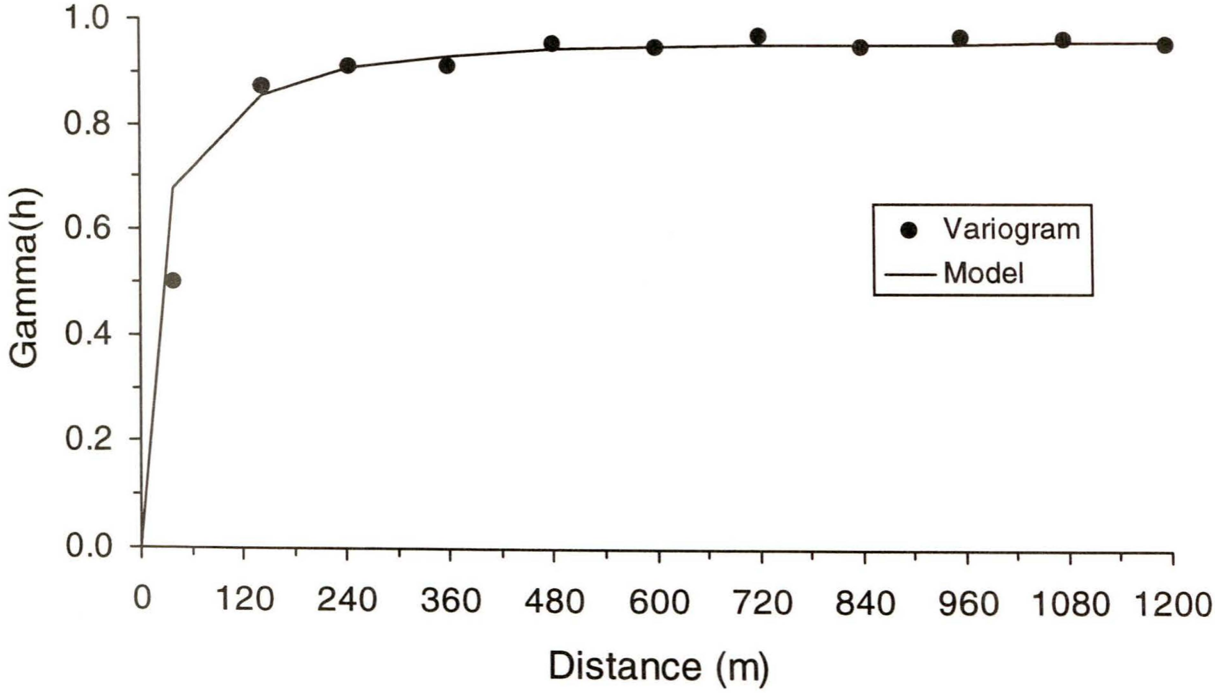


Figure 4.—*Variogram and fitted model for the WERF.*

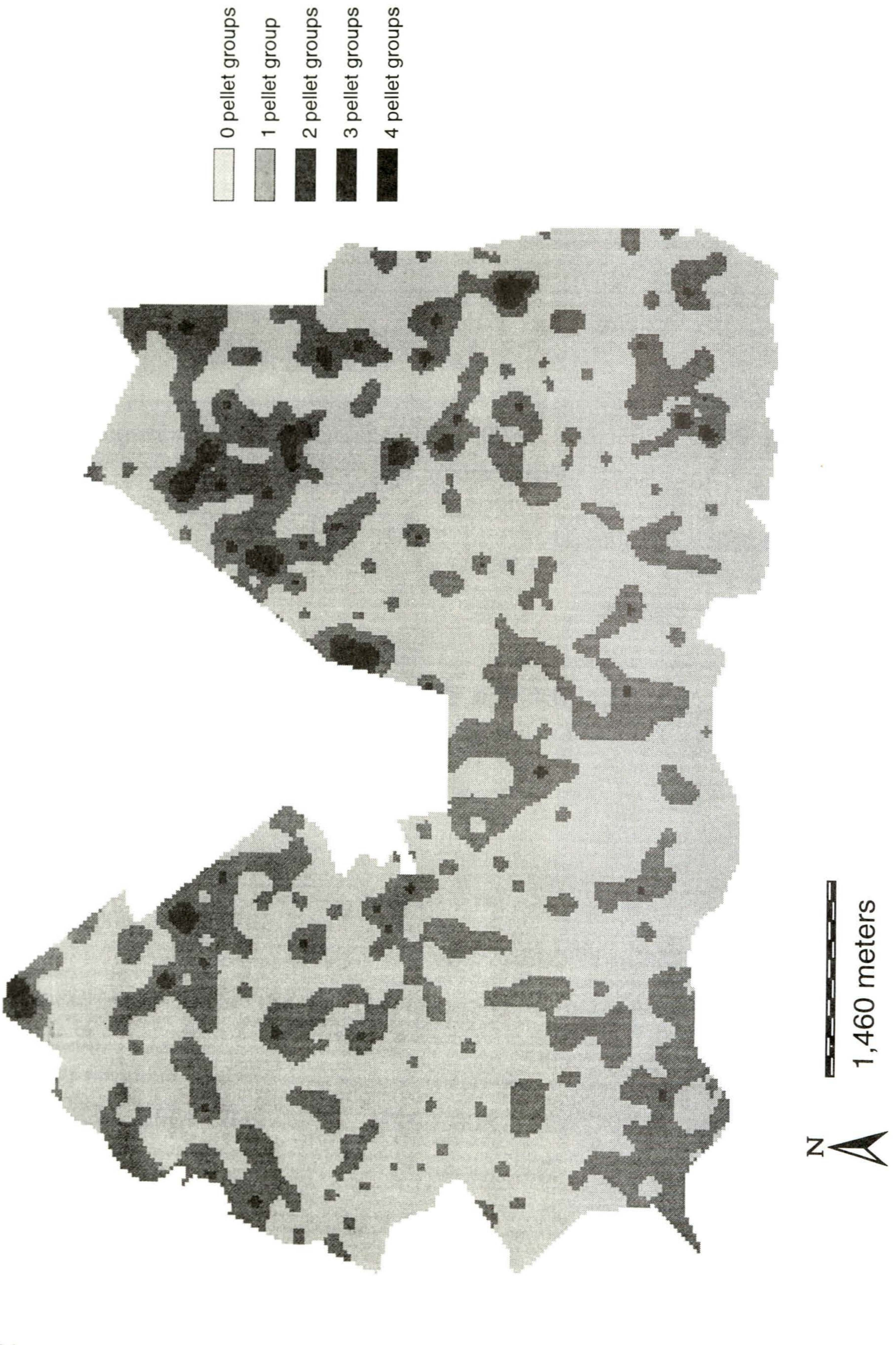

0 pellet groups
1 pellet group
2 pellet groups
3 pellet groups
4 pellet groups
1,460 meters
N

Figure 5.—*Kriged estimate map for the WVUF.*

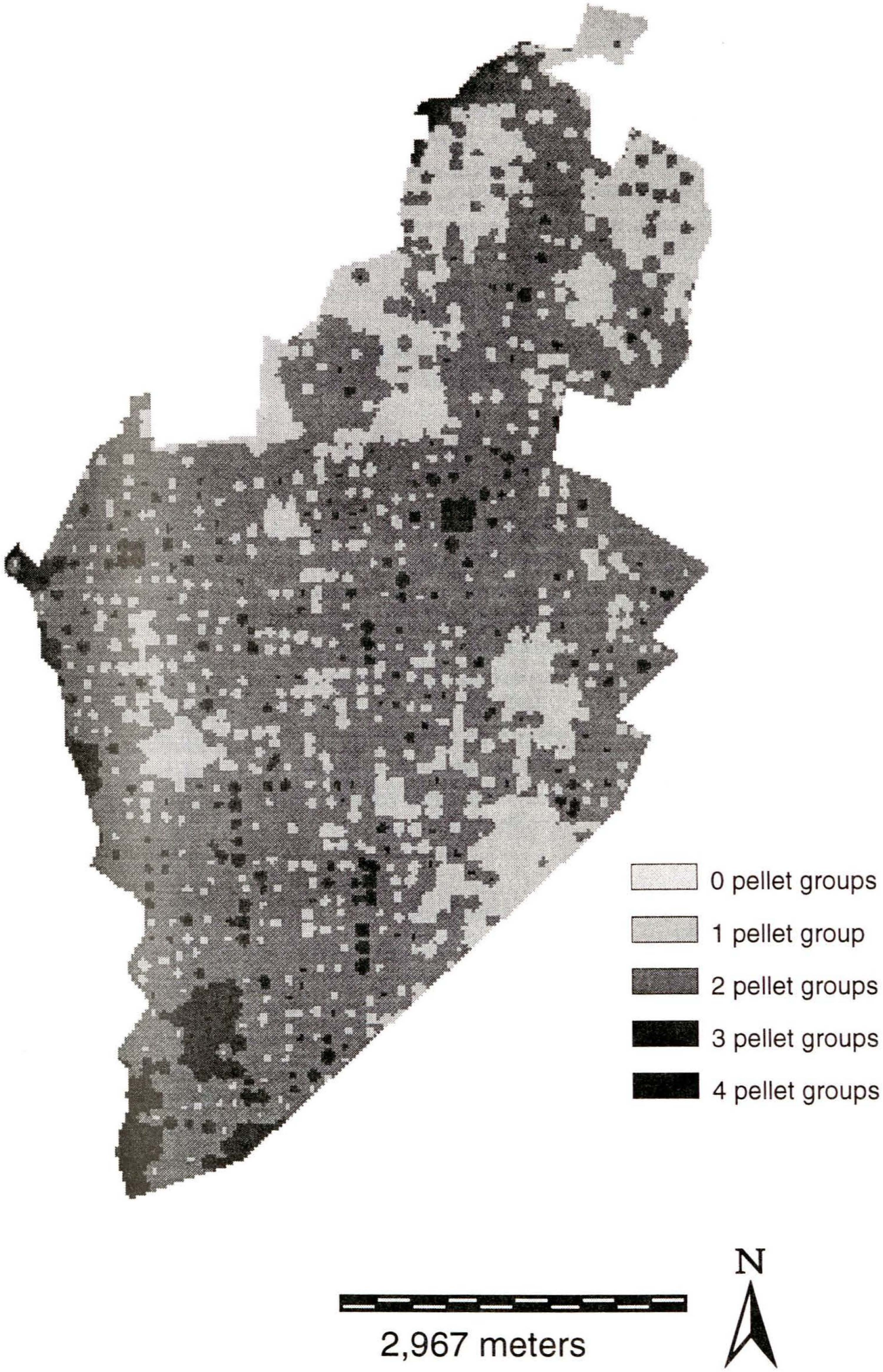

0 pellet groups
1 pellet group
2 pellet groups
3 pellet groups
4 pellet groups
2,967 meters
N

Figure 6.—*Kriged estimate map for the WERF.*

proximity to adjacent plots than was actually planned. These data could have been omitted; however, we chose to retain them because they provide important information about spatial dependencies in the data at smaller separation distances. The WVUF data included 132 pairs of plots that were separated by an average distance of 42.31 m and 5,832 pairs separated by an average distance of 142.76 m. Numbers of additional pairs ranged from 9,928 at a separation distance of 244.40 m to 37,576 at the maximum separation distance of 1,200.19 m. The WERF data included 78 pairs separated by an average distance of 40.25 m and 5,426 separated by an average distance of 144.03 m. Numbers of pairs ranged from 9,946 at 244.76 m to 39,144 at approximately 1,200 m.

The variogram models for both forests included two nested structures, indicating that on both sites there existed local and regional trends in the data. Both structures used in the construction of the WVUF variogram model were of exponential form. The first had a range of 231 m and sill of 0.415; the second had a range of 156 m and sill of 0.015. The first structure describes the relatively steep increase in variability among pairs of plots separated by an average distance of less than 231 m. The second structure models the gradual increase in variability between separation distances from 231 to 387 m. Ninety-seven percent of the combined sill, or maximum variability, is reached at an average separation distance of 231 m; the remaining 3 percent occurs between 231 and 387 m.

The model used to describe the variogram of the WERF data was more complex. The first structure had a spherical form and describes the steep increase in variability between separation distances of less than 92 m. This structure accounts for 79 percent of the combined sill of 0.95. The second structure, of exponential form, describes a gradual increase in variability to a separation distance of approximately 577 m. It is important to note that the first structure is heavily influenced by the 78 pairs at very close separation distance.

Overall, pellet group counts made on the WERF were more spatially variable than those made on the WVUF. The combined sill of 0.95 for the WERF data was more than double the 0.43 sill for the WVUF data. This was expected given the differences in the sites. The WVUF is relatively uniform and continuous with harvest units clustered along a rudimentary road system. Most of the site has not been actively managed for 80 years, and little of the total area is in early successional stages. In addition, the forest is heavily hunted and deer populations are not excessive (no quantitative estimate of deer densities is available at this time). In contrast, the WERF has been heavily impacted by both partial timber harvest and dispersed regeneration harvests. The habitat is more variable, and more of the total area is covered by young forest. The area is also heavily bisected by a well-developed road system; however, the WERF is gated and hunting is prohibited. Deer populations are consequently much higher on the WERF; the excessive browsing of woody understory vegetation and paucity of herbaceous vegetation indicate that the site is saturated with deer.

The relative lack of sample data at small separation distances, combined with the strong localized trend in the WERF data, appears in the kriged estimate map as an "egg crate" effect; the overwhelming influence of the most proximal samples caused localized depressions and peaks in the kriged estimates. This problem apparently could be rectified through more intensive sampling. Based on the results of the variography, sampling intensity may have to be more than doubled.

In contrast, the kriged estimates for the WVUF reveal clearly defined areas of heightened deer activity. Less overall variability, a weaker local trend, and a stronger regional trend enabled us to produce an apparently useful predictive map of baseline deer activity patterns. In general, the peaks in estimated pellet counts correspond quite well with known canopy disturbances. For example, peak deer activity occurred in the northeastern lobe of the forest, which was impacted by high overstory mortality in 1990-1991 followed by timber salvage operations. The spike of activity at the tip of the northwestern lobe corresponds with a gas pipeline right-of-way. Peaks in the southeastern corner correspond with recent timber harvest operations.

CONCLUSIONS

In general, pellet group data appear to contain enough spatial contagion to allow the production of estimate maps using two-dimensional ordinary point kriging. Although the estimates have not yet been validated, it appears that spikes in pellet group densities on the WVUF correspond to overstory disturbances and resultant increased availability of woody browse. The results on the WERF were less conclusive and generally indicate that the technique may be less useful in areas of extremely high deer population and variable habitat. However, based on the presence of localized spatial dependence in the small number of samples collected at less than 240 m, it appears that a followup study at higher sampling intensity is warranted before concluding that the technique cannot be used on the WERF or similarly impacted sites.

ACKNOWLEDGMENTS

We would like to thank Diane M. Krishon who supervised the collection of the field data and performed preliminary data manipulations. Thanks also go to field technicians, Julie Swisher, Kendra Teter, and Michael Henry. Richard Odom, Sally Lane, and Sarah Clapman with Westvaco provided data layers and technical advice. This study was completed thanks to a grant from Westvaco and financial support from the West Virginia University Division of Forestry.

LITERATURE CITED

Alverson, W.S.; Waller, D.M.; Solheim, S.L. 1988. Forests too deer: edge effects in Northern Wisconsin. Conservation Biology. 2: 348-358.

Behrend, D.F.; Mattfeld, G.F.; Tierson, W.C.; Wiley, J.E., III. 1970. Deer density control for comprehensive forest management. Journal of Forestry. 68: 695-700.

Bennett, L.J.; English, P.F.; McCain, R. 1940. A study of deer populations by use of pellet-group counts. Journal of Wildlife Management. 4: 398-403.

Biondi, F.; Myers, D.E.; Avery, C.C. 1994. Geostatistically modeling stem size and increment in an old-growth forest. Canadian Journal of Forest Research. 24: 1354-1368.

Bowersox, T.W.; Storm, G.L.; Tzilkowski, W.M. 1993. Developing regeneration in woodlots at Gettysburg National Military Park. In: Proceedings, 9th Central hardwood forest conference; 1993 March 8-10; West Lafayette, IN: Purdue University: 409-417.

deCalesta, D. 1994. Impact of deer on interior forest songbirds in northwestern Pennsylvania. Journal of Wildlife Management. 58: 711-718.

Deutsch, C.V.; Journel, A.G. 1998. GSLIB: geostatistical software library and user's guide. New York, NY: University Press. 369 p.

Eberhardt, L.; Van Etten, R.C. 1956. Evaluation of the pellet group count as a deer census method. Journal of Wildlife Management. 20(1): 70-74.

Eyre, F. H., ed. 1980. Forest cover types of the United States and Canada. Washington, DC: Society of American For.esters. 148 p.

Ford, W.M.; Johnson, A.S.; Hale, P.E. 1994. Nutritional quality of deer browse in southern Appalachian clearcuts and mature forests. Forest Ecology and Management. 67: 149-157.

Ford, W.M.; Johnson, A.S.; Hale, P.E.; Wentworth, J.M. 1993. Availability and use of spring and summer woody browse by deer in clearcut and uncut forests in the southern Appalachians. Southern Journal of Applied Forestry. 17: 116-119.

Fuller, T.K. 1991. Do pellet counts index white-tailed deer numbers and population change? Journal of Wildlife Management. 55(3): 393-396.

Goovaerts, P. 1997. Geostatistics for natural resources evaluation. New York, NY: Oxford University Press. 483 p.

Gribko, L.S.; Liebhold, A.M.; Hohn, M.E. 1995. Model to predict gypsy moth (Lepidoptera: Lymantriidae) defoliation using kriging and logistic regression. Environmental Entomology. 24: 529-537.

Hohn, M.E. 1988. Geostatistics and petroleum geology. New York, NY: Van Nostrand Reinhold.

Hohn, M.E.; Liebhold, A.M.; Gribko. L.S. 1993. A geostatistical model for forecasting the spatial dynamics of defoliation caused by the gypsy moth, *Lymantria dispar* (Lepidoptera: Lymantriidae). Environmental Entomology. 22(5): 1066-1075.

Horsely, S.B.; Marquis, D.A. 1983. Interference by weeds and deer with Allegheny hardwood reproduction. Canadian Journal of Forest Research. 13: 61-69.

Isaaks, E.H.; Srivastava, R.M. 1989. An introduction to applied geostatistics. New York, NY: Oxford University Press. 561 p.

Johnson, A.S.; Hale, P.E.; Ford, W.M.; Wentworth, J.M.; French, J.R.; Anderson, O.F.; Pullen, G.B. 1995. White-tailed deer foraging in relation to successional stage, overstory type and management of southern Appalachian forests. American Midland Naturalist. 133: 18-35.

Jordan, J.S. 1967. Deer browsing in northern hardwoods after clearcutting. Res. Pap. NE-57. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 15 p.

Kemp, W.P.; Kalaris, T.M.; Quimby, W.F. 1989. Rangeland grasshopper (Orthoptera: Acrididae) spatial variability: macroscale population assessment. Journal of Economic Entomology. 82: 1270-1276.

Liebhold, A.M.; Zhang, X.; Hohn, M.E.; Elkinton, J.S.; Ticehurst, M.; Benzon, G.L.; Campbell, R.W. 1991. Geostatistical analysis of gypsy moth (Lepidoptera: Lymantriidae) egg mass populations. Environmental Entomology. 20: 1407-1417.

Marquis, D.A. 1974. The impact of deer browsing on Allegheny hardwood regeneration. Res. Pap. NE-308. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 8 p.

Marquis, D.A. 1981. The effects of deer browsing on timber production in Allegheny hardwood forests of northwestern Pennsylvania. Res. Pap. NE-475. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 10 p.

Marquis, D.A.; Eckert, P.L.; Roach, B.A. 1976. Acorn weevils, rodents, and deer all contribute to oak-regeneration difficulties in Pennsylvania. Res. Pap. NE-356. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 5 p.

Marquis, D.A.; Grisez, T.J. 1978. The effect of deer exclosures on the recovery of vegetation in failed clearcuts on the Allegheny Plateau. Res. Note NE-270. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 5 p.

McCormick, L.H.; Groninger, J.W.; Penrod, K.A.; Ristau, T.E. 1993. Deer exclusion effects on understory development following partial cutting in a Pennsylvania oak stand. In: Proceedings, 9th Central hardwood forest conference; 1993 March 8-10; West Lafayette, IN: Purdue University: 418-427.

Neff, D.J. 1968. The pellet group count technique for big game trend, census, and distribution: a review. Journal of Wildlife Management. 23: 597-614.

Pannatier, Y. 1996. VARIOWIN: software for spatial data analysis in 2D. New York, NY: Springer-Verlag. 91 p.

Pauley, E.F.; Nodvin, S.C.; Nicholas, N.S.; Rose, A.K.; Coffey, T.B. 1996. Vegetation, biomass, and nitrogen pools in a spruce-fir forest of the Great Smoky Mountains National Park. Bulletin of the Torrey Botanical Club. 123: 318-329.

Pelletier, D.; Parma, A.M. 1994. Spatial distribution of Pacific halibut (Hippoglossus stenolepis): an application of geostatistics to longline survey data. Canadian Journal of Fish and Aquatic Science. 51: 1506-1518.

Redding, J. 1987. Impact of deer on forest vegetation and timber production in northern Pennsylvania. In: Proceedings, Symposium on deer, forestry, and agriculture: interactions and strategies for management; 1987 June 15-17; Warren, PA: Allegheny Section of the Society of American Foresters: 23-32.

Robertson, G.P. 1987. Geostatistics in ecology: interpolating with known variance. Ecology. 68(3): 744-748.

Robinette, W.L.; Ferguson, R.B.; Gashwiler, J.S. 1958. Problems involved in the use of deer pellet group counts. Transactions of the North American Wildlife Conference. 23: 411-425.

Rossi, R.E.; Mulla, D.J.; Journel, A.G.; Franz, E.H. 1992. Geostatistical tools for modeling and interpreting ecological and spatial dependence. Ecological Monograph. 62: 277-314.

Shafer, E.L.; Grisez, T.J.; Sowa, E. 1961. Results of deer exclosure studies in northeastern Pennsylvania. Res. Note NE-121. Upper Darby, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 6 p.

Sheffer, D.E. 1987. Deer herd management in Pennsylvania. In: Proceedings, Symposium on deer, forestry, and agriculture: interactions and strategies for management; 1987 June 15-17; Warren, PA: Allegheny Section of the Society of American Foresters: 138-142.

Storm, G.L.; Yahner, R.H.; Cottam, D.F.; Vecello, G.M. 1989. Population status, movements, habitat use, and impact of white-tailed deer at Gettysburg National Historic Site, Pennsylvania. Tech. Rep. NPS/MAR/NRTR - 89/043. Springfield, VA: National Technical Information Service, U.S. Department of Interior, National Park Service. 513 p.

Stout, S.L.; deCalesta, D.S.; Horsley, S.B.; Nowak, C.A.; Redding, J.C. 1995. Ecosystems management research in hardwood forests dominated by deer. In: Proceedings, 10th Central hardwood forest conference; 1995 March 5-8; Morgantown, WV. Gen. Tech. Rep. NE-197. Radnor, PA: U.S. Department of Agriculture, Forest Service Service, Northeastern Forest Experim ent Station. 577 p.

Tierson, W.C.; Patric, E.F.; Behrend, D.F. 1966. Influence of white-tailed deer on the logged northern hardwood forest. Journal of Forestry. 64: 801-805.

Tilghman, N.G. 1989. Impacts of white-tailed deer on forest regeneration in northwestern Pennsylvania. Journal of Wildlife Management. 53: 524-532.

Trumbull, V.L.; Zielinski, E.J.; Aharrah, E.C. 1989. The impact of deer browsing of the Allegheny forest type. Northern Journal of Applied Forestry. 6: 162-165.

Van Etten, R.C.; Bennett, C.L., Jr. 1965. Some sources of error in using pellet-group counts for censusing deer. Journal of Wildlife Management. 29: 723-729.

Villard, M.A.; Maurer, B.A. 1996. Geostatistics as a tool for examining hypothesized declines in migratory songbirds. Ecology. (1): 59-68.

Wentworth, J.M.; Johnson, A.S.; Hale, P.E.; Kammermeyer, K.E. 1990. Seasonal use of clearcuts and food plots by white-tailed deer in the southern Appalachians. Proceedings of the Annual conference of Southeastern Fish and Wildlife Agencies. 44: 215-223.

Conservation and Restoration of Forested Wetlands: New Techniques and Perspectives

James Johnston, Steve Hartley, and Antonio Martucci

Abstract.—A partnership of state and federal agencies and private organizations is developing advanced spatial analysis techniques applied for conservation and restoration of forested wetlands. The project goal is to develop an application to assist decisionmakers in defining the eligibility of land sites for entry in the Wetland Reserve Program (WRP) of the U.S. Department of Agriculture. The WRP is one of the most successful programs in restoring wetlands on marginal agriculture lands. For this effort, three 7.5-minute quadrangles in Louisiana (Indian Lake, Newlight, and Saranac) were used as a pilot area. A data set of thematic and remotely sensed data was collected and organized inside a geographic information system (GIS) ArcView project. By using the ArcView's internal scripting language (Avenue), the project has been customized for WRP needs. Procedures that make easier data display and analysis operations were then implemented.

The Lower Mississippi River Valley (LMRV) has experienced dramatic forested wetland losses (over 80 percent) in the last century as a result of clearing for agriculture and urban expansion. Federal and state efforts are oriented towards promoting wetland conservation and restoration programs that preserve these valuable resources for future generations. Advanced spatial analysis techniques, i.e., decision support geographic information systems (GIS), improve the resource manager's capability of defining potential sites for wetland restoration or conservation. This paper illustrates the results of a GIS demonstration project and advanced spatial analysis techniques applied to the WRP. Partners of this project are the U.S. Department of Agriculture (USDA)/Natural Resources Conservation Service (NRCS), Alexandria, LA; U.S. Fish and Wildlife Service (USFWS)/Ecological Services Office, Lafayette, LA; The Nature Conservancy (TNC), Baton Rouge, LA; and U.S. Geological Survey (USGS), National Wetlands Research Center (NWRC), Lafayette, LA.

WRP is a voluntary program to restore and protect wetlands on private property. It is administered by the USDA's NRCS, in consultation with the Farm Service Agency (FSA) and other federal agencies. Landowners who enter the program receive financial support to take their marginal agricultural land out of production for conversion to wetlands or for enhancement and/or protection of existing wetlands. The ultimate goal of WRP is to enroll under the program about 1 million acres nationwide. The states of Tennessee, Louisiana, Mississippi, and Alabama will benefit mostly from this program.

GEOGRAPHIC INFORMATION SYSTEMS (GIS) SOLUTIONS AND DATA

Geographic information systems (GIS) is a technology that allows the assembly, storage, manipulation, display, and output of geographical and related tabular data. Investigations and analyses on different but geographically related data sets may be performed by using overlay or query techniques. Additionally, GIS can use different types of data and information from different sources and in different forms. The primary purpose of the GIS application is to present geographic and tabular data in one comprehensive, easy-to-use application. This WRP application incorporates those capabilities that enable the user to better utilize and analyze incoming environmental data with existing data sets.

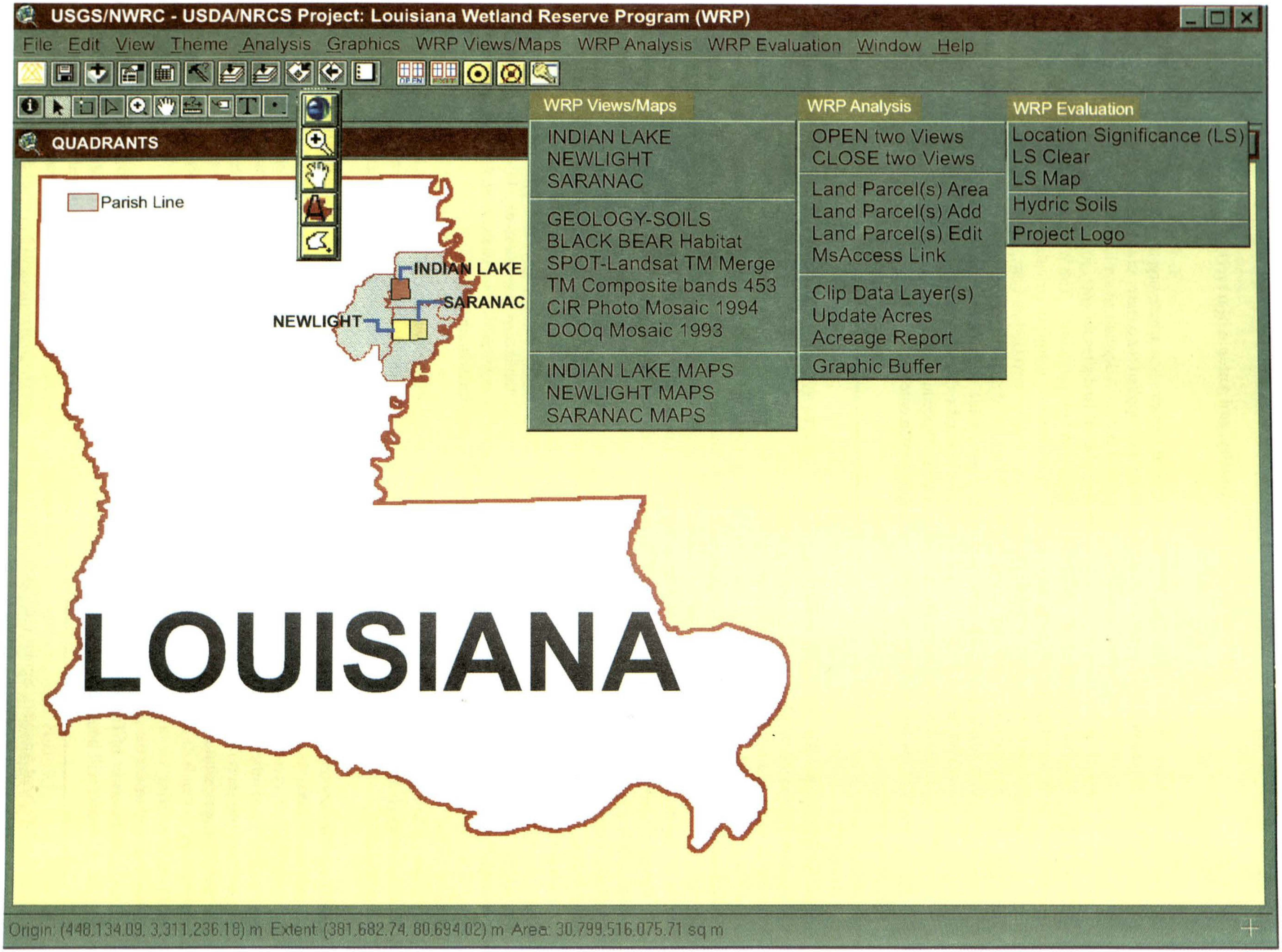
Three 1:24,000-scale USGS quadrangles were selected: Indian Lake, Newlight, and Saranac, which are located in the northeast section of Louisiana (fig. 1).

The data sets that have been collected from existing sources or created for this project are:

1. WRP, Conservation Reserve Program (CRP), Farmers Home Administration (FmHA), Wildlife Management Area (WMA) Lands, and National Wildlife Refuges (NWR),
2. Soil Types, Hydric Soils, and Geology (1:24,000) (fig. 2),
3. Black Bear Habitat,
4. The Louisiana GAP Vegetation Data - Classified Landsat 5 Thematic Mapper imagery, along with other auxiliary data sets organized into 23 major vegetation groups and land-use categories,
5. SPOT Panchromatic (10 m resolution),
6. Landsat 5 Thematic Mapper, False Color Composite 4,5,3 (1993) (25 m resolution),

---

Chief, Spatial Habitat Analysis, Senior GIS Specialist, and Visiting Scientist, U.S. Geological Survey, National Wetlands Research Center, Lafayette, LA, USA.


USGS/NWRC - USDA/NRCS Project: Louisiana Wetland Reserve Program (WRP)
File
Edit
View
Theme
Analysis
Graphics
WRP Views/Maps
WRP Analysis
WRP Evaluation
Window
Help
OPEN
EXIT
QUADRANTS
Parish Line
INDIAN LAKE
SARANAC
NEWLIGHT
LOUISIANA
WRP Views/Maps
INDIAN LAKE
NEWLIGHT
SARANAC
GEOLOGY-SOILS
BLACK BEAR Habitat
SPOT-Landsat TM Merge
TM Composite bands 453
CIR Photo Mosaic 1994
DOOq Mosaic 1993
INDIAN LAKE MAPS
NEWLIGHT MAPS
SARANAC MAPS
WRP Analysis
OPEN two Views
CLOSE two Views
Land Parcel(s) Area
Land Parcel(s) Add
Land Parcel(s) Edit
MsAccess Link
Clip Data Layer(s)
Update Acres
Acreage Report
Graphic Buffer
WRP Evaluation
Location Significance (LS)
LS Clear
LS Map
Hydric Soils
Project Logo

```
Origin: (448,134.09, 3,311,236.18) m Extent: (381,682.74, 80,694.02) m Area: 30,799,516,075.71 sq m
```

Figure 1.—*Study area and sample ArcView scripts for Wetland Reserve Program demonstration project.*

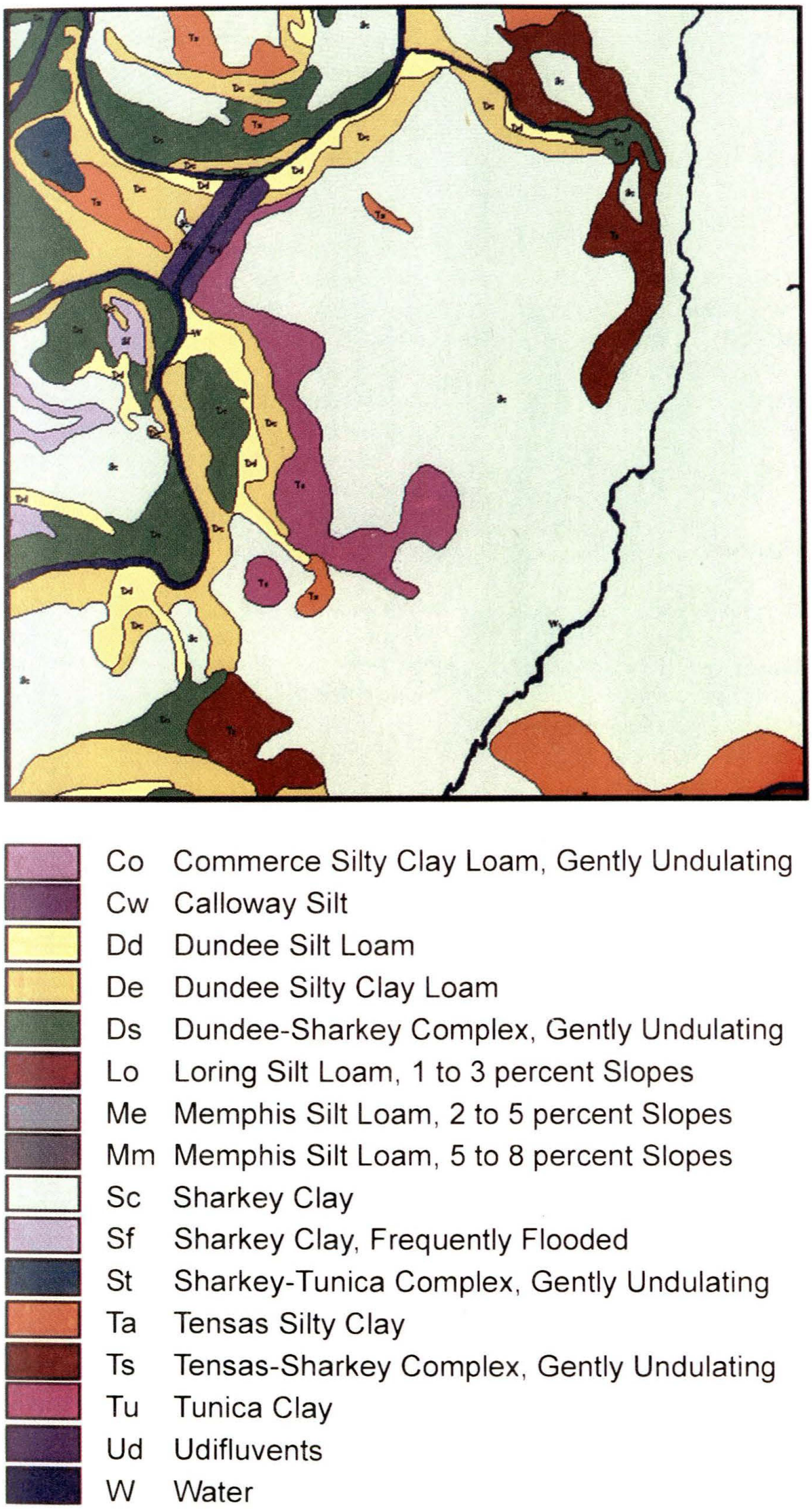

Co Commerce Silty Clay Loam, Gently Undulating
Cw Calloway Silt
Dd Dundee Silt Loam
De Dundee Silty Clay Loam
Ds Dundee-Sharkey Complex, Gently Undulating
Lo Loring Silt Loam, 1 to 3 percent Slopes
Me Memphis Silt Loam, 2 to 5 percent Slopes
Mm Memphis Silt Loam, 5 to 8 percent Slopes
Sc Sharkey Clay
Sf Sharkey Clay, Frequently Flooded
St Sharkey-Tunica Complex, Gently Undulating
Ta Tensas Silty Clay
Ts Tensas-Sharkey Complex, Gently Undulating
Tu Tunica Clay
Ud Udifluvents
W Water

Figure 2.—*Example of detail soils data (1:24,000 scale) used for project.*

7. SPOT Panchromatic (1995)-Landsat Thematic Mapper (1993) merge (10 m resolution),
8. Mosaic of scanned 1995 color infrared photos,
9. Mosaic of scanned 1945-46 black and white historical photos,
10. Digital Orthophoto Quads (DOQ) (Newlight and Saranac) and mosaic of DOQ Quarters (Indian Lake),
11. Digital Raster Graphics (DRG) of 1:24,000 USGS quadrangles,
12. State and parish boundaries (digital),
13. USGS Hydrologic Unit boundaries,
14. Soil and Water Conservation District boundaries,
15. Oil and gas well locations, and
16. USGS Digital Line Graphs (DLG's) (1:100,000) for:
    - * Transportation
    - * Hydrology
    - * Pipelines
    - * Railroads
    - * State and parish boundaries.

ARC VIEW PROJECT

Using Environmental Systems Research Institute (ESRI) ArcView 3.0a GIS software, an application was developed to organize the available data sets and allow land resource managers to access sophisticated display and analysis tools without being GIS experts. ArcView, combined with Avenue scripting language, offers the possibility of integrating and visualizing geographic and tabular data into a complete analysis system while creating a highly user-friendly windows environment. This was considered a primary goal because, unfortunately, GIS is rarely used due to its prohibitive cost (hardware and software) and learning curve.

ArcView Graphical User Interface (GUI) has been customized for this project using menus and menu items, as well as added buttons and tools. Land resource managers can access sophisticated display and analysis tools without being GIS experts. The GUI also allows the user to select information layers, open display windows, and perform some complex and multi-phase tasks in one or more steps. Input and selection message boxes guide the user to complete processes successfully.

DISPLAY AND ANALYSIS TOOLS

Several scripts have been developed to provide display and analysis tools. Thematic information and images can be displayed separately or overlaid over the same area. Additionally, a routine has been created to automatically open (and close) two views with user-selected themes to display. Zooming or panning in one view will display both views at the new extent. The purpose of this implementation is to provide users an easier way to display and compare two data sets over the same location. An interesting application is the comparison of aerial photography of two different dates (fig. 3). Using theme polygons on temporary boundary (graphic), a routine that clips layers and performs simple statistical analysis (acreage, perimeter, or length) has been developed. It is a multi-step procedure requiring users to input values or make selections from lists.

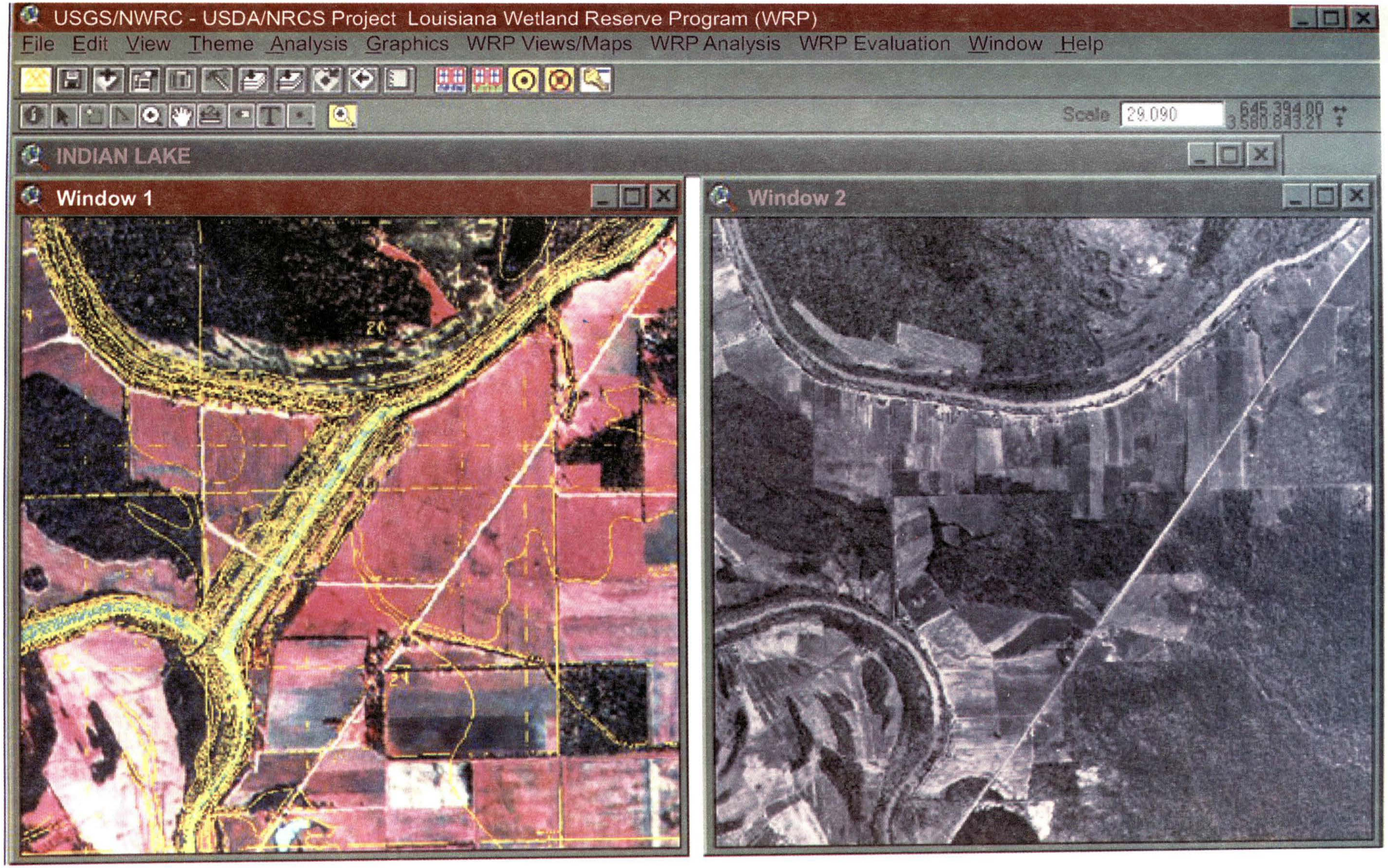
This project is also a test to explore possible integration between ArcView and an external relational database package like Microsoft (MS) Access 97. The purpose is to extend the capability of ArcView to display, input, and process tabular information by using MS Access interface, which is powerful and much easier to use. A simple MS Access application containing tables and input forms allows a person to display and update tabular information related to each enrolled WRP parcel. In particular, it stores functional assessments of assigned wetlands (according to several parameters of water quality, habitat, risk, and hydrology factors). Dynamic Data Exchange (DDE) technology, supported by ArcView, is the mechanism of communication between the two applications. Figure 4 is an example of interface designed to display and input land and landowner information, and point value of ranking factors.

Lastly, routines that allow a user to input or to update land parcels by using on-screen digitizing or GPS coordinates have been developed. With high-resolution aerial photography as a backdrop, the actual boundaries can be readily identified and drawn. Based on the Louisiana WRP ranking procedure, land parcels can be buffered to estimate the proximity to protected areas. We can also buffer lands already enrolled in conservation programs and create a map of distance.

CONCLUSION

The WRP, as well as the other wetland restoration and conservation programs, can greatly benefit from the use of GIS technology and spatial analysis techniques. The ESRI/ArcView GIS software has been successfully used for creating a user-friendly display and analysis tool of different types of geographical and tabular data. Avenue scripts allowed flexibility and simplification of repetitive and difficult tasks, making available to users and decisionmakers a tool that can help them analyze and evaluate sites for wetland restoration or conservation. The project is constantly being updated with new data sets and WRP-oriented spatial analysis routines. By increasing the cooperation among developers and final users, better solutions can be found.

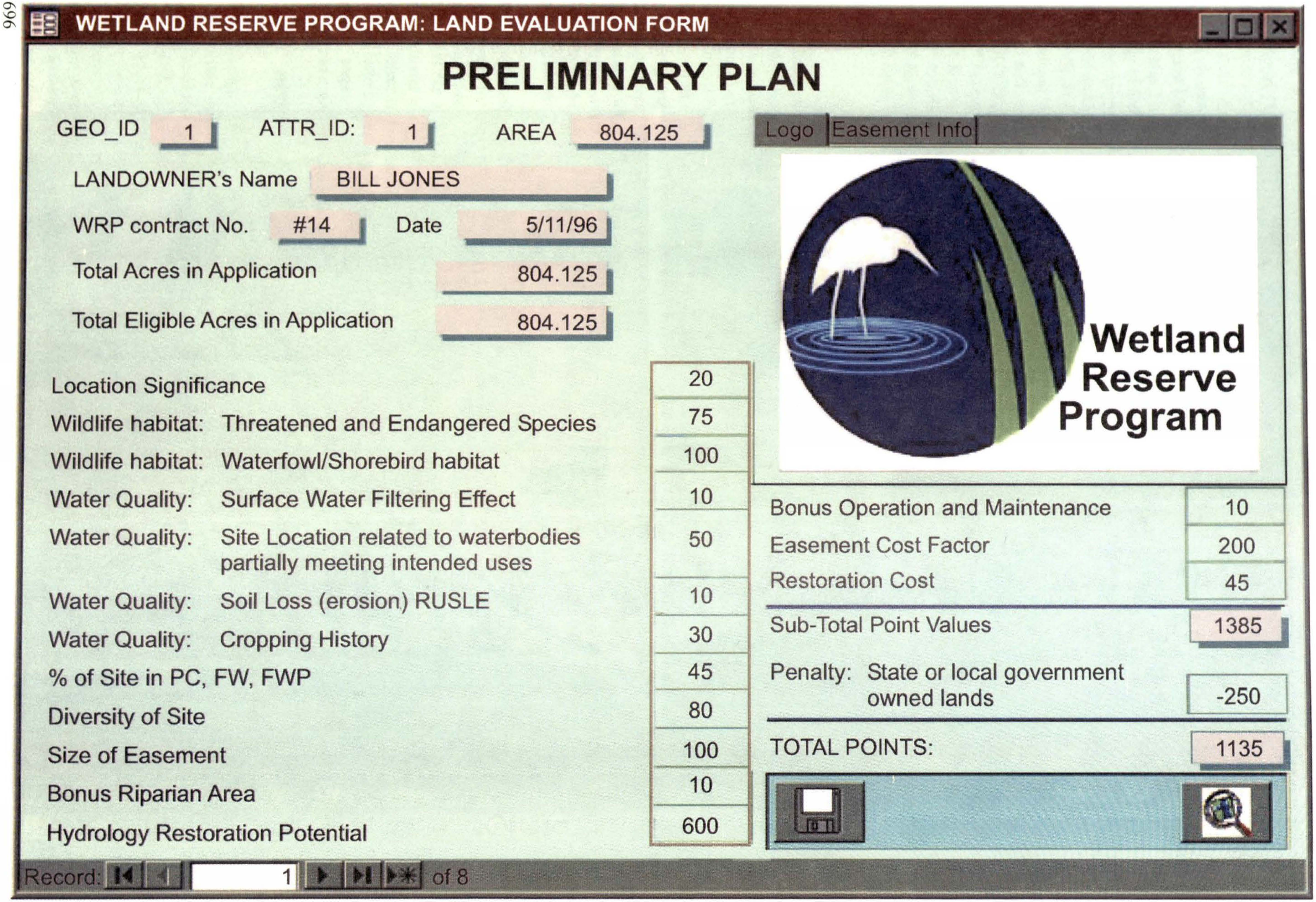
In closing, there is an expectation of increasing the integration of typically GIS vector functions and raster functions made available by ArcView's Spatial Analyst and 3D Analyst extension; to "open" this ArcView-based project to other applications (basically relational databases) will improve the application capability.


USGS/NWRC - USDA/NRCS Project Louisiana Wetland Reserve Program (WRP)
File Edit View Theme Analysis Graphics WRP Views/Maps WRP Analysis WRP Evaluation Window Help
INDIAN LAKE
Window 1
Window 2
20
21

Scale 29.090

645,394.00
3,580,843.21

Figure 3.—*Side by side photographs displaying an area in 1995 (left) versus 1945 (right). Note clearing of forested wetlands for agriculture.*



WETLAND RESERVE PROGRAM: LAND EVALUATION FORM

PRELIMINARY PLAN

GEO_ID 1 ATTR_ID: 1 AREA 804.125

LANDOWNER's Name BILL JONES

WRP contract No. #14 Date 5/11/96

Total Acres in Application 804.125

Total Eligible Acres in Application 804.125

Location Significance	20
Wildlife habitat: Threatened and Endangered Species	75
Wildlife habitat: Waterfowl/Shorebird habitat	100
Water Quality: Surface Water Filtering Effect	10
Water Quality: Site Location related to waterbodies partially meeting intended uses	50
Water Quality: Soil Loss (erosion) RUSLE	10
Water Quality: Cropping History	30
% of Site in PC, FW, FWP	45
Diversity of Site	80
Size of Easement	100
Bonus Riparian Area	10
Hydrology Restoration Potential	600

Bonus Operation and Maintenance	10
Easement Cost Factor	200
Restoration Cost	45
Sub-Total Point Values	1385
Penalty: State or local government owned lands	-250
TOTAL POINTS:	1135

Figure 4.—*Example of WRP Land Evaluation Form to rank parcels for the Program.*

An Inventory of Multipurpose Avenue Trees of Urban Chandigarh, India

R.K. Kohli, H.P. Singh, and Daizy R. Batish

Abstract.—Trees in urban ecosystems play a very significant role in environmental protection by checking air and noise pollutants, abating wind, and handling many other functions. In India, Chandigarh is the most modern and environmentally safe city and qualifies to be called a GREEN CITY because of its rich tree component. This is so in spite of its high population density, currently over 9,443 people per square km, perhaps the highest in the country. It has nearly 42,000 trees growing along the roads in a systematic manner. The drives are identified with the type of multipurpose tree species. Nearly 66 tree species (over half indigenous) are seen along the roadsides; these trees provide shade, timber, fuel, fodder, fruit, medicine, and other benefits. In addition, the city is decorated with 11 gardens harboring over 200 types of trees.

The concept of urban forestry includes not only aesthetics, but also functions for environmental and socio-economic uplift. Trees in urban areas are very important in view of increasing population, urbanization, pollution levels, and diminishing forest areas. Trees serve many useful purposes, especially in urban areas where they improve air quality (Smith 1980) and microclimate (Nowak 1995), reduce noise levels, abate wind, and reduce stress on human beings (Ulrich 1985). They also improve aesthetic, architecture, landscape, wildlife, and recreational elements of the city (Kohli *et al.* 1996). In cities, the tree component could be established usually in the following three ways, depending upon the prevailing situations:

1. As clusters on the outskirts of cities/towns mainly for recreational visits of the locals, nesting and roosting of birds, shelter for game animals, and a sink for the city pollutants. This is more likely for old cities like Calcutta, New York, or Delhi that are relatively unplanned and overpopulated.
2. As managed vegetation on roadsides, in parks, gardens, homesteads, premises of institutions, industries, and religious places. This is likely for cities like Chandigarh and Islamabad, which are planned and not very old.
3. As a major biotic component when cities are carved within the forested areas, as in Scandinavian countries, which have low population density. Although the tree density in these countries is relatively high, the diversity remains limited since it results from the manipulation of natural forest dominants. On the other hand, in the first two alternatives, because of man's wider choices, the multipurpose species find relatively more representation.

This presentation aims at describing the rich diversity of multipurpose trees along the roads of a modern Indian city—Chandigarh—which in spite of its very high population density qualifies to be called an Environmentally Safe and Beautiful City.

THE CITY

In India, only a few cities have been systematically planned, especially in the post-independence period. Chandigarh (30° 42' 25" N; 76° 48' 30" E; 333 m MSL), the capital of two progressive states Punjab and Haryana, is one such city. It was designed by French architect Le Corbusier in 1955. This city of 114 km^2 has an urban area of 78 km^2 (approx. 40.11 sq. miles), divided into 47 sectors, each approximately 246 acres (1,200 x 800 m). It is surrounded by 35 small rural areas covering 36 km^2

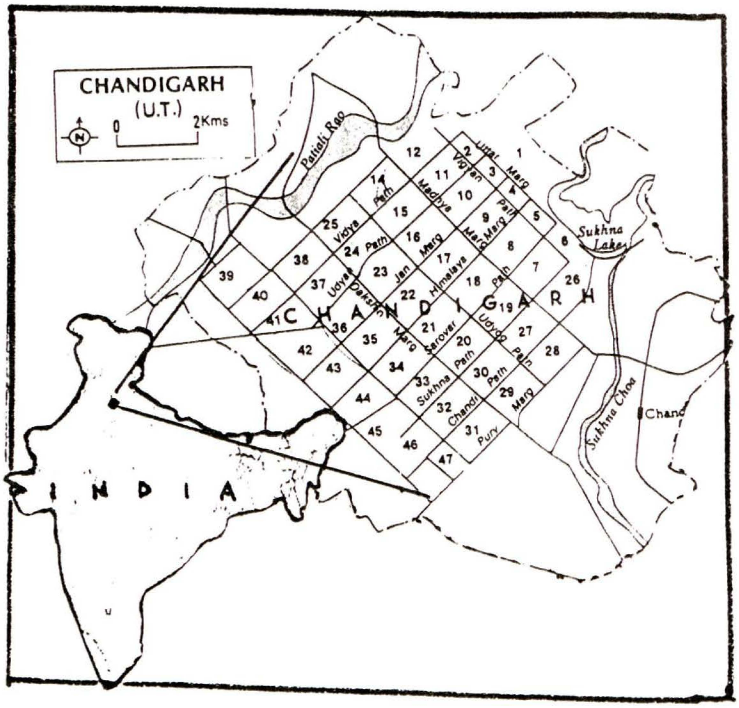


Figure 1.—*Chandigarh, India.*

Professor, Research Associate, and Lecturer, respectively, Unit of Ecology and Forestry, Botany Department, Panjab University, Chandigarh - 160 014, India.

Table 1.—*Demographic characteristics of urban Chandigarh*

Population (projected as on March 1, 1998)	821,282 (575,829)*
Decadel population growth	60.89 percent (42.16 percent)*
Area	78 km^2
Population density projected as on March 1, 1998	10,529 per km^2 (7,382 per km^2)*
Total state-owned forests	77.71 acre
Private forest	Nil
Total livestock (projected as on March 1, 1998)	61,072 (52,190)*
Total annual rainfall	1,220 mm
Temperature range	1.7 to 44.2 °C

* as per 1991 census.

The city was designed for 0.3 million people, but has over 0.82 million people in addition to a floating population of 0.22 million from the adjoining satellite towns of Panchkula (Haryana state) and Mohali (Punjab state) (table 1). The rate of population growth of the city had been unexpectedly rapid. In spite of the high population density of 10,529 persons per km^2, air pollution is still at a sub-threshold level. Chandigarh is still considered an environmentally safe city, which is one of the reasons for its fast population influx. The city has alluvial soil, and it was a land of mango (*Mangifera indica*) and *Ficus* trees and crops of wheat, maize, and sugarcane. The locals on the slopes of the Shiwalik foothills have given it the greenery of neighborhood, mountain rivulets, and fresh air.

City Roads

Basically, there are six type of roads, besides foot paths and cycle tracks, in the city. These are classified as: **V_1** (state highways connecting city with other cities and towns); **V_2** (arterial roads dividing the city into three parts north, middle, and south); **V_3** (roads running on the outer periphery of the sectors, i.e., dividing the city into various sectors); **V_4** (sector dividing roads or market roads splitting the sector into two halves); **V_5** (circular roads within sectors); and **V_6** (access roads to houses).

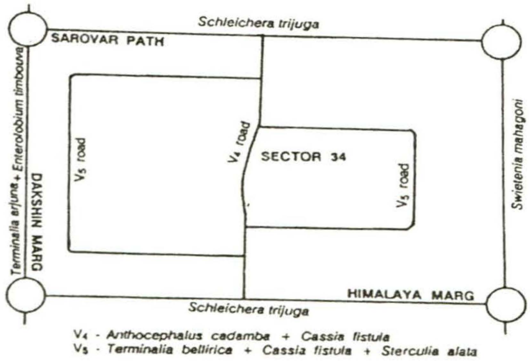

Schleichera trijuga
SAROVAR PATH
Terminalia arjuna + Enterolobium timbouva
DAKSHIN MARG
V5 road
V4 road
SECTOR 34
V5 road
Swietenia mahagoni
HIMALAYA MARG
Schleichera trijuga
V4 - Anthocephalus cadamba + Cassia fistula
V5 - Terminalia bellirica + Cassia fistula + Sterculia alata

Figure 2.—*Example section map.*

THE TREESCAPE

The city has no natural forest or a climax ecosystem. Agriculture or the agroforestry component is also totally lacking. Likewise, the social forestry, commercial, and farm forestry components are also missing. Nevertheless, the organized green character of Chandigarh is perhaps the richest (compared to any other Indian city), with ornamental, horticultural avenue trees and shrubs. Throughout the year, some part of the city is manifested with colorful landscape and blooming trees. The roads are mostly identified with the type of trees planted along their sides. For instance:

V_2 - Southern Drive (Dakshin Marg) has *Terminalia arjuna* throughout
V_2 - Northern Drive (Uttar Marg) has *Acrocarpus fraxinifolius*
V_3 - Sukhna Lake Drive has *Tamarindus indica*
V_3 - University Drive (Vidya Path) has *Heterophragma roxburghii*
V_4 - Sector 34 has *Anthocephalus cadamba* + *Cassia fistula*
V_5 - Sector 34 has *Terminalia bellerica* + *Cassia fistula* + *Sterculia alata*

Because of the longevity of trees, the relatively long time required for planting and later for acquiring maturity, and their varied impact on the city residents, tree species have been selected with care. The major considerations for the selection were:

- shape and size of the leaf and crown
- height of the tree
- tree character (deciduous or evergreen)
- aesthetics and architecture
- color and timing of flowering
- constraints of time, transport, and the availability of healthy planting material
- climatic adaptability

The city has around 100 types of trees, of which 66 are avenue trees planted along roadsides, 11 are forest trees and shrubs, and about 20-25 types of trees are grown in the premises of city residents. The city is also characterized by the presence of 11 gardens covering a total area of about 400 acres and having nearly 240 types of trees (Kohli *et al.* 1994).

In all, there are about 42,000 avenue trees, in addition to about 32,000 in small clusters and in gardens and over 50,000 in the premises of institutions and houses. Depending on the site, the roadside trees of different height and architecture are in single, double, or multiple rows. An inventory of the available avenue trees here in terms of their English name, botanical name, family and center of origin, flowering months in Chandigarh, and major uses is tabulated below (table 2).

Bougainvillea shrubs with a variety of colored flowers on the road dividers is a characteristic of the city. In addition, the city has 11 gardens each with a good number of trees of many types (table 3). Although these trees have not been planted for economic use, most of them have many uses.

Table 2.—*Species planted along roadsides as avenue trees in Chandigarh, India*

S. No	Botanical name	Family & country of origin (in parentheses)	English name(s)	Flowering months in Chandigarh	Economic importance
1.	*Acacia auriculiformis*	Mimosaceae (Australia)	Australian Acacia or Phyllode, Australian Wattle	September to November	Ornamental tree; fuel wood
2.	*Acrocarpus fraxinifolius*	Caesalpiniaceae (Indo-Malaya)	Pink or red cedar, Shingle tree	December to February	Timber for making tea chests
3.	*Adina cordifolia*	Rubiaceae (India)	Saffron teak	June to July	Shade, Wood for carving, making combs, writing tablets and ornamental platters
4.	*Albizzia lebbeck*	Mimosaceae (Tropical Asia)	East Indian walnut tree, parrot or fry wood or lebbeck, woman's tongue or sizzling tree	April to August	Wood for furniture; leaves and branches as fodder, bark and seeds medicinal, also yields gum
5.	*Albizzia odoratissima*	Mimosaceae (Sub-Himalayan tracts of India)	Black siris	April to June	Wood for furniture; leaves and branches as fodder, bark and seeds medicinal, also yields gum
6.	*Albizzia procera*	Mimosaceae (India)	Stone siris, white siris	August to September	Timber, fodder, medicinal use, also yields charcoal and gum
7.	*Alstonia scholaris*	Apocynaceae (Penninsular India)	Scholar or devil's or dita bark tree, shaitan wood tree	December to March	Medicinal (vermifuge), wood used for making slates and blackboards, bark bitter and astringent
8.	*Anthocephalus chinensis* (=*A. cadamba*)	Rubiaceae (India)	Kadam	July to September	Wood for making match boxes, pulp; flowers sacred, fruits edible
9.	*Artocarpus heterophyllus*	Moraceae (India)	Jack fruit	November to January	Fruit and seeds edible, yields a yellow dye, timber for furniture
10.	*Azadirachta indica*	Meliaceae (India, probably Burma also)	Margosa tree, neem	April to May	Medicinal, insecticidal, yields neem oil used in soaps, pastes, tooth powder etc., nematicidal
11.	*Barringtonia acutangula*	Barringtoniaceae = Lecythidaceae (Sub-Himalayan regions of India)	Indian oak	May to July	Ornamental, bark used for stupefying fishes, wood used for making boats and well-work etc.

(table 2 continued on next page)

(table 2 continued)

S. No	Botanical name	Family & country of origin (in parentheses)	English name(s)	Flowering months in Chandigarh	Economic importance
12.	*Bauhinia purpurea*	Caesalpiniaceae (Foot hills of Himalayas)	Camel hoof, tree bean, geranium tree, purple bauhinia tree, mountain ebony	October to December	Leaves for fodder, floral buds as food
13.	*Bauhinia variegata*	Caesalpiniaceae (Hilly parts of India)	Variegated or buddhist bauhinia, orchid tree	March to April	Floral buds edible, pods and leaves used for fodder, sacred tree, timber wood
14.	*Bischofia javanica*	Euphorbiaceae = Bischofiaceae (Indo-Malaya)	Java cedar, bishop wood, west Indian cedar, vinegar wood, red cedar	March to April	Timber for pile, foundation, railways etc., dye for rattan stuff
15.	*Callistemon viminalis*	Myrtaceae (Australia)	Scarlet bottle brush	March to August	Ornamental
16.	*Cassia fistula*	Caesalpiniaceae (India)	Golden shower tree, pudding pipe tree, Indian laburnum, purging cassia	May to July	Ornamental, seeds laxative, pods and bark yield dye and tan, dark brown sweet pulp of fruit is strong purgative
17.	*Cassia javanica*	Caeselpiniaceae (Java & Sumatra)	Java cassia, siboosook	May to July	Ornamental timber used in Java, fruit purgative
18.	*Cassia nodosa*	Caesalpiniaceae (Burma)	Pink mohur	May to July	Ornamental, timber for house building, fruit purgative
19.	*Cassia renigera*	Caeselpiniaceae (Burma)	Burmese pink cassia	April to May	Ornamental
20.	*Cassia siamea*	Caeselpiniaceae (Indo-China)	Kassod, djoowar	November to December	Ornamental, timber for bridges, props and telegraph poles also used as firewood
21.	*Chorisia speciosa*	Bombacaceae (Brazil, Argentina)	Mexican silk cotton tree	October to November	Ornamental, yields kapok and silky cotton
22.	*Chukrasia tabularis*	Meliaceae (Indo-Malaya, Sri Lanka & China)	Bastard cedar, Indian redwood, chittagong wood	March to May	Source of Chittagong wood for furniture, bark for tanning, flowers yield dye
23.	*Crateva nurvala* (=*C. religiosa*)	Capparidaceae (Deciduous forests of India)	Caper tree, sacred barna	April to May	Ornamental, sacred, bark and leaves medicinal, pulp of fruit mixed with mortar gives strong cement
24.	*Dalbergia sissoo*	Papilionaceae (India)	Rose wood, south Indian red wood, black wood tree	March to May	Shade, timber
25.	*Delonix regia*	Caeselpiniaceae (Madagascar)	Flame, flamboyant, royal poinciana or gold mohur, holy ghost, peacock flower tree	April to August	Ornamental

(table 2 continued on next page)

(table 2 continued)

S. No	Botanical name	Family & country of origin (in parentheses)	English name(s)	Flowering months in Chandigarh	Economic importance
26.	*Drypetes roxburghii*	Euphorbiaceae (Indo-Malaya)	Child-life tree, lucky bean tree, Indian amulet, wild olive tree	March to May	Ornamental tree, leaves as fodder
27.	*Emblica officinalis*	Euphorbiaceae (Tropical Asia)	Emblic myrobalan, cicca emblica	March to April	Fruit edible, bark yields dye, bark and fruit have medicinal value
28.	*Enterolobium timbouva*	Mimosaceae (Brazil)	Timbouva	March to June	Ornamental tree
29.	*Eucalyptus citriodora* *E. tereticornis*	Myrtaceae (Australia)	Blue gum tree, fever tree lemon-scented or citron-scented eucalypt	April to May (generally)	Source of timber, paper pulp, essential oils for cosmetic and pharmaceutical industries, ornamental tree
30.	*Eugenia jambolana*	Myrtaceae (India)	Indian blackberry, black plum, java plum	April to June	Fruit edible and has medicinal value, timber, fuelwood, dyes
31.	*Ficus benghalensis*	Moraceae (Sub-Himalayan Indian forests)	Banyan tree	Throughout the year	Religious, bark and aerial roots yield fiber, leaves as fodder, shade
32.	*Ficus benjamina*	Moraceae (Indo-Malaya, China)	Weeping or willow or java or golden fig, java willow, Benjamin tree	Throughout the year	Ornamental avenue tree
33.	*Ficus infectoria*	Moraceae (India)	Palakh	May to July	Ornamental, shade
34.	*Ficus religiosa*	Moraceae (India)	The bo-tree, The peepul tree	October to September (almost year round)	Sacred tree to Hindus and Buddhists, leaves used for miniature paintings, host for lac and silk worm insects, ornamental
35.	*Grevillea robusta*	Proteaceae (Eastern Australia)	Silver oak, silky oak	April to May	Ornamental, avenue, timber
36.	*Heterophragma roxburghii*	Bignoniaceae (India)	Monkey tail tree	March to June	Ornamental
37.	*Jacaranda mimosifolia*	Bignoniaceae (Brazil, Argentina)	Jacaranda, mimosa leafed jacaranda	April to May	Ornamental and avenue tree
38.	*Kigelia pinnata*	Bignoniaceae (Tropical Africa)	Sausage or fetish tree, cucumber tree	April to July	Ornamental and purgative
39.	*Koelreuteria apiculata*	Sapindaceae (Eastern China)	Chinese tallow tree	October to November	Ornamental, flowers source of yellow dye & medicine, seeds used as beads

(table 2 continued on next page)

(table 2 continued)

S. No	Botanical name	Family & country of origin (in parentheses)	English name(s)	Flowering months in Chandigarh	Economic importance
40.	*Lagerstroemia flos-reginae* (= *L. speciosa*)	Lythraceae (Western Ghats of India)	Pride of India, queen's flower, queen's crepe myrtle	May to October	Ornamental, timber, leaves and fruit for tanning
41.	*Lagerstroemia parviflora*	Lythraceae (India)	Lendia	April to June	Source of gum, fiber, timber, charcoal, used in tanning
42.	*Lagerstroemia thorelli*	Lythraceae (South East Asia)	Queen's flower, pride of India	May to November	Ornamental
43.	*Litchi chinensis*	Sapindaceae (China)	Litchi	April to May	Fruit edible and highly priced
44.	*Madhuca indica*	Sapotaceae (Indo-Malaya, Indo-China, Australia)	Indian butter tree, illipe nut tree, wild sapota tree	April to May	Seeds and Flowers yield oil (Phulwa oil), seed cake used as worm killer, flowers edible and yield a strong spirit, bark useful for tanning
45.	*Mangifera indica*	Anacardiaceae (India, Burma)	Mango, cupid's favorite, spring tree, cuckoo's joy	March to April	Fruit edible, timber, medicinal
46.	*Millettia ovalifolia*	Papilionaceae	Moulmein rosewood (Indo-China & Malaya)	April to May	Ornamental, insecticidal, fish and arrow poison
47.	*Millingtonia hortensis*	Bignoniaceae (Burma & Malaya)	Indian cork tree, jasmine tree	September to November	Ornamental, yields low quality cork, source of timber, leaves as substitute for opium in cigarettes
48.	*Mimusops elengi*	Sapotaceae (Indo-Malaya, Sri Lanka)	Indian medlar, bullet-wood tree, elengi	March to May	Ornamental, bark and fruit medicinal, fruit edible, timber, flowers used in perfumery and making garlands, oil from seeds
49.	*Polyalthia longifolia*	Annonaceae (South India and Sri Lanka)	Mast tree, Indian fir, asoka tree	February to May	Indian Sacred tree and ornamental
50.	*Pongamia pinnata*	Papilionaceae (Indo-Malaya)	Indian beech, poonga oil plant	May to July	Ornamental, shade, yields oil (Honga oil), source of timber and fuel wood, ash of tree used for dyeing
51.	*Populus nigra* *P. deltoides*	Salicaceae (Europe, North-West Asia, North China, Canada)	Poplar, black poplar, eastern cottonwood	November to January	Source of timber, resins and medicines
52.	*Pterospermum acerifolium*	Sterculiaceae (India)	Kanak - champa muchkand	March to May	Ornamental, leaves as fodder, for making plates & packing material, timber
53.	*Roystonea regia*	Arecaceae (West Indies)	Bottle palm, royal palm, mountain glory, palmiste	August to October	Ornamental

(table 2 continued on next page)

(table 2 continued)

S. No	Botanical name	Family & country of origin (in parentheses)	English name(s)	Flowering months in Chandigarh	Economic importance
54.	*Salmalia malabarica* (=*Bombax ceiba*)	Bombacaceae (India)	Silk-cotton tree, cotton wood tree, semal tree	February to March	Ornamental, medicinal, source of gum, timber, flowers edible, source of fiber, yield cotton (Kapok)
55.	*Sapium sebiferum*	Euphorbiaceae (China)	Chinese tree, vegetable tree, tallow tree	June to August	Ornamental, shade, fatty seed covering (Tallow) is used for candles and soap, leaves yield black dye
56.	*Schleichera oleosa*	Sapindaceae (Foot hills of Himalayas and Sri Lanka)	Lac tree, honey tree, Ceylon oak, kosumba tree	April to May	Seeds source of Macassar oil used in candles, hair-dressing, batik work, fruit edible, host of lac insect, yields priced Kusum lac
57.	*Spathodea campanulata*	Bignoniaceae (Tropical and Central Africa)	Uganda flame or African tulip or scarlet fountain or scarlet bell or squirt or syringe or bell flambeau tree	April to June	Ornamental
58.	*Sterculia alata*	Sterculiaceae (Tropical Asia)	Buddha's coconut	February to March	Ornamental
59.	*Sweitenia mahagoni*	Meliaceae (Central America)	Spanish mahogany, The mahogany	April to May	Timber
60.	*Tamarindus indica*	Caesalpiniaceae (Africa)	Indian date, The tamarind tree	June to August	Timber, fruit edible, used in culinary preparations, leaves yield dye
61.	*Tecoma argentea*	Bignoniaceae (Tropical America)	-	January to April	Ornamental
62.	*Tecomella undulata*	Bignoniaceae (India)	Wavy leafed tecomella	April to June	Ornamental, source of fuelwood
63.	*Terminalia arjuna*	Combretaceae (India)	Arjun tree	April to June	Bark and ash used in dyeing and tannin, gum, bark, leaves and fruit are medicinal (used for blood pressure)
64.	*Terminalia bellirica*	Combretaceae (India)	Belleric or bastard myrobalan, bedda nut	May to June	Timber, fruit source of tannin, black dye, ink, medicinal
65.	*Thespesia populnea*	Malvaceae (India)	Tulip or portia or umbrella or bhendi tree	November to January	Ornamental, hardwood is used for gun stocks
66.	*Toona ciliata* (= *Cedrella toona*)	Meliaceae (Indo-Malaya)	Toon or happy tree, moulmein or red or Singapore cedar, sandal nim Indian mahogany	March to April	Ornamental, good timber, flowers yield sulphur colored dye called basanti, bark is medicinal

Table 3.—*Gardens of Chandigarh*

Sr. No.	Garden	location (sector)	Area (acres)	Tree types (no.)
1	Rajindra Park	1	150	12
2	Bougainvillea Garden	3	30	26
3	Bulbous Garden	9	35	12
4	Leisure Valley	10	70	30
5	Museum and Art Gallery	10	7.5	23
6	Botanical Garden	14	16	209
7	Zakir Rose Garden	16	32	43
8	Terraced Garden	33	10	42
9	Topiary Garden	35	8	29
10	36 Garden	36	35	52
11	Hibiscus Garden	36	65	23

(from Kohli *et al.* 1994)

Of the above 66 tree types, over half are of Indian origin. Literally, every tree can be regarded as multipurpose. However, apart from the service of moderating microclimate, stabilizing soil, providing fuel for the poor, removing air pollutants, and reducing noise pollution in the cities, the avenue trees of Chandigarh perform other multiuse functions. Upon categorizing one finds 39 serving as ornamental, 34 yielding timber, 15 yielding food, 9 fodder, 6 fibers, 35 providing material for direct industrial (including medicinal) use, while miscellaneous functions like shade to pedestrians, shelter to wildlife, dyeing and tanning, etc., is provided by 33 types of the trees.

ACKNOWLEDGMENTS

The authors thank Prof. P.K. Khosla, Vice-Chancellor, HP Agricultural University, Palampur, HP, India, and Member Executive Board, IUFRO, and Dr. M.P. Bansal, Principal Scientist, Division of Physiology and Ecology, Forest Research Institute, Dehradun, India, for critically reviewing and making suggestions for improving this manuscript.

LITERATURE CITED

Kohli, R.K. 1996. Need and planning for avenue trees in cities - a Chandigarh experience. In: Ecofriendly trees for urban beautification. Solan, India: Indian Society of Tree Scientists and National Horticultural Board: 39-49.

Kohli, R.K.; Arya, K.S.; Singh, H.P.; Dhillon, H.S. 1994. Tree directory of Chandigarh. Chandigarh, India : Dayanand National Academy of Environmental Sciences. 230 p.

Kohli, R.K.; Singh, H.P.; Sharma, A.; Batish, D.R. 1996. Panorama of trees in India. In: Ecofriendly trees for urban beautification. Solan, India: Indian Society of Tree Scientists and National Horticultural Board: 1-69 (appendix).

Nowak, D.J. 1994. Air pollution removal by Chicago's Urban Forests. In: Chicago's urban forest ecosystem. Gen. Tech. Rep. NE-186. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 65-85.

Smith, W.H. 1981. Air pollution and forests. New York: Springer. 397 p.

Kellomaki, S. 1976. Tree stands in urban noise abatement. Silva Fennica. 3: 237-256.

A Strategy for Monitoring Swiss Needle Cast and Assessing its Growth Impact in Douglas-fir Plantations of Coastal Oregon

Doug Maguire, Alan Kanaskie, and Mike McWilliams

Abstract.—Many Douglas-fir plantations along the north coast of Oregon are exhibiting severe symptoms of Swiss needle cast disease (SNC). These symptoms include premature loss of foliage, abundant fungal pseudothecia on needles, yellowing of foliage, and apparent reduction in diameter and height growth. The development of the disease and its impacts on growth are currently being monitored at three different levels: (1) annual aerial surveys to determine extent of SNC symptoms; (2) plantation surveys to assess the extent of SNC damage and to ground-truth aerial surveys; and (3) intensively measured plots to monitor SNC development and growth impacts.

THE PROBLEM

Over 2 million hectares (5 millions acres) of commercial timberland in the Pacific Northwest are occupied by young stands (≤40 years) of Douglas-fir (Oswald *et al.* 1986). The growth, yield, and overall health of these plantations is tremendously important to the people of Oregon and Washington. A wide variety of silvicultural treatments has been applied operationally and experimentally in these stands, and yield forecasting tools for intensively managed plantations of Douglas-fir are constantly in a state of further development and improvement. Although insect and disease damage can wreak havoc on predictions of future yield, coastal Douglas-fir has been relatively free of extensive problems that complicate management (except for root diseases in some areas). Swiss needle cast (SNC), a foliage disease that affects only Douglas-fir, has emerged recently as a significant problem for Douglas-fir planted along the north coast of Oregon (Kanaskie *et al.* 1996). Many plantations of young Douglas-fir within this region began exhibiting severe symptoms of SNC approximately 6-10 years ago. These symptoms included premature loss of foliage, abundant fungal pseudothecia on needles, yellowing of foliage, smaller average size of needles, and apparent reduction in diameter and height growth. Although a range in symptom severity and assumed disease intensity was observed, the magnitude of growth loss associated with various foliar symptoms was largely unknown. Growth losses are quite apparent upon casual observation in severely damaged plantations, but may be more subtle in plantations with fewer visual symptoms. The problem may be particularly critical in young plantations (10-30 years) due to limited silvicultural options and the economic costs of starting over with a new plantation. Without the option of harvesting commercial size classes, replacement of pre-commercial, declining, SNC-impacted stands with productive stands consisting of resistant varieties or species would constitute a tremendous loss of investment; yet, without corrective action, significant yield losses will continue to accrue.

The overall effort to assess and monitor Douglas-fir stand condition with respect to SNC consists of three interactive projects: an aerial survey, a ground-based plantation survey, and a growth impact study. These projects, as well as others that will not be discussed here, are conducted under the auspices of the Swiss Needle Cast Cooperative (SNCC) at Oregon State University. This research cooperative was initiated in January 1997 at the prompting of several key industry and agency foresters. In 1996, prior to formation of the SNCC, the Oregon Department of Forestry (ODF) initiated an aerial survey to assess the extent of apparent damage from SNC. This effort has continued on an annual basis in coordination with SNCC-sponsored projects. The objectives of the aerial survey were:

1. To identify and map areas of Douglas-fir forest with obvious symptoms of SNC in the Oregon Coast Range; and
2. To monitor change over time in the amount of forest with visible symptoms of the disease.

The ODF also launched a ground-based survey of SNC severity in Douglas-fir plantations to meet four additional objectives:

1. To ground-truth areas mapped by aerial survey;
2. To describe the extent and severity of damage from SNC in randomly selected 10- to 30-year-old Douglas-fir plantations in the Coast Range of western Oregon;

Assistant Professor, Department of Forest Resources, Oregon State University, Corvallis, OR, USA; Forest Pathologist, and Survey Specialist, Oregon Department of Forestry, Salem, OR, USA, respectively.

3. To identify tree attributes that were best able to discriminate among different levels of SNC intensity; and
4. To provide SNC assessment of plantations analyzed for growth impacts.

The growth impact study was funded directly by the SNC to determine the magnitude of both stand-level and regionwide growth losses. The specific objectives included:

1. To estimate the current losses of stem volume growth across the range of SNC severity;
2. To screen various tree and foliage attributes that may be identifiable as indices of severity and corresponding growth losses; and
3. To develop quantitative links among attributes that can be monitored in aerial surveys, low-intensity ground surveys, and intensively measured growth plots.

PAST WORK

Damage from SNC has frequently been observed on Douglas-fir grown outside of its natural range, first in Europe in the early part of the century, and more recently in Christmas tree plantations throughout North America and in timber stands in New Zealand (Hansen *et al.* 1996). Although some European research was motivated by concern about growth losses, relatively little work has been accomplished to date on estimation of growth impact, especially within the natural range of Douglas-fir and across a gradient in disease severity. Height growth of SNC-affected Douglas-fir in the Pacific Northwest has been estimated at 50-70 percent of normal height growth, corresponding to as much as a 30 percent volume growth loss (USDA FS 1983, as cited in Russell *et al.* 1986). In New Zealand, basal area growth of stands experiencing Douglas-fir decline is as low as 50 percent of the basal area growth of stands exhibiting no decline (Beekhuis 1978). Forest scientists in New Zealand have pointed out that, although the Swiss needle cast fungus (*Phaeocryptopus gaeumannii*) is associated with declining Douglas-fir stands, it is uncertain whether this pathogen is the cause of the decline or an aftereffect of other causes (see discussion of decline in growth, Forest Research Institute 1978).

Ultimately any height and basal area growth losses must be translated into volume growth losses to facilitate economic analysis and to choose among management options. Studies of volume growth losses from SNC have apparently not been conducted, or at least not published, for the Pacific Northwest; yet this information is essential to providing an economic basis by which to judge the need for, or economic benefits of, an aggressive control or rehabilitation program. Likewise, an analysis of growth responses to SNC can establish a biological basis by which to assess silvicultural options. In New Zealand, thinning did not reduce *Phaeocryptopus* infection or increase needle retention, despite the healthier appearance of thinned stands (Hood and Sandberg 1979). In northwestern Oregon, there is concern that thinning may exacerbate the negative growth effects of SNC, perhaps through a thinning shock effect (sensu Harrington and Reukema 1983)

METHODOLOGY

Aerial Survey

The Oregon Department of Forestry and the USDA Forest Service Region 6 Forest Health Protection program conducted cooperative aerial surveys of SNC damage in coastal Oregon in April and May of 1996, 1997, and 1998. Discoloration caused by SNC is most visible from late winter until shortly after bud break in spring; peak discoloration occurs in late April and early May. Flights were made at 450-600 m (1,500 to 2,000 feet) above the terrain, following north-south lines separated by 3.2 km (2 miles). The flight lines extended from the Columbia River in the north to a latitude even with Bandon in the south, and extended up to 38 km (24 miles) inland. The eastern and southern limits of the survey were dictated by the disappearance of SNC-induced discoloration.

Areas with obvious discoloration were drawn onto 1:100,000 scale topographic maps and classified as either lightly or heavily discolored and later transferred onto the ODF GIS. The resulting GIS layer portrayed the geographic extent of SNC and provided an estimate of the area with apparently severe SNC.

Plantation Surveys

Target Population

The target population for the plantation survey and the growth impact study was defined by stand condition and geographical location (Kanaskie *et al.* 1996, Oregon Department of Forestry 1998). Specifically, the sample was drawn from the population of Douglas-fir plantations between 10 and 30 years of total age and located within 29 km (18 miles) of the coast, north of Newport and south of Astoria.

A list of plantations meeting these criteria was assembled, and plantations were selected from this list with probability proportional to size (area). The target population included 4,504 plantations covering 75,929 ha (187,545 acres). The sample included 77 plantations covering 2,783 ha (6,873 acres). Each plantation was assessed for SNC intensity, and all landowners were contacted for any information available on management history of the unit.

The plantation surveys provided verification that aerially mapped polygons were Douglas-fir stands with severe SNC symptoms, facilitating refinement of GIS-generated maps depicting stands with obvious SNC damage. The field procedure involved assigning each plantation a walk-through rating for degree of discoloration and an overall rating based on color, foliage retention, and apparent growth reduction. In addition, a five-point transect was established in a representative area of the plantation. Sample points were separated by 15 m (50 ft), and the two dominant or codominant Douglas-fir trees nearest the point but on opposite sides of the transect line were selected as sample trees. Each tree was assessed for the following indicators of SNC damage: presence or absence of fruiting bodies, recent height growth reductions, degree of yellowing, and needle retention. Degree of yellowing and needle retention were estimated for the fifth whorl from the top as well as for each third of the tree live crown. In the 1998 plantation surveys, three variables used in the USDA Forest Health Monitoring program were also included: crown density, foliage transparency, and crown dieback.

Growth Impact Study

Field and Lab Work

Phase 1.—The growth impact study complemented the ODF aerial and plantation surveys by collecting additional information on fixed-area plots in 70 of the 77 plantations selected for survey. The third sample point on each plantation survey transect was flagged, marked with a PVC stake, and subsequently used as the center of a 0.02-ha (0.05-ac) plot (10.6-m or 26.3-ft radius) on which all trees were measured for dbh. The four Douglas-fir trees with the largest dbh and the two with the smallest dbh were felled, as were the two Douglas-fir closest to the midrange of the diameter distribution. Each felled tree, except for of the two smallest Douglas-fir, was measured for total height, height to crown base, and cumulative height growth (height of each bud scale scar, at or just above each annual branch whorl). Two stem disks were removed from each of the felled Douglas-fir trees, one at breast height and one at crown base. These disks were labeled and stored in a plastic bag for transport to the lab. Finally, a sample branch was collected from the fourth largest Douglas-fir tree on each plot. This sample branch was identified as the southernmost branch in the fifth whorl from the top of tree. After the diameter of the branch was measured, it was cut from the tree flush with the stem, and one of the secondary branches in the third whorl down from the primary branch tip was removed, placed in a plastic bag, stored on ice up to 4 days, and then frozen in the lab. The remaining portions of the branch were placed in a plastic bag and transported to the lab for drying and weighing.

Breast height stem disks were brought to the lab and measured for annual radial growth (nearest 0.5 mm) on the two radii forming the long axis of the disk and on the two radii forming the axis perpendicular to the longest. Four sapwood radii (nearest 0.5 mm) were recorded on the same two axes. Secondary branches were kept frozen until they could be analyzed for specific leaf area by measuring projected area (nearest 0.001 cm^2) and dry weight (nearest 0.0001 g) of 50- needle subsamples of 1-, 2-, and 3-yr-old needles separately. Pseudothecia of *Phaeocryptopus gaeumannii* were also counted on 10 needles from each 50-needle subsample. Pseudothecia counts represented the number of occluded stomates out of the centermost 100 in the second row of stomates to the right of the needle midrib, with the petiole pointing downward.

The remaining branch samples were clipped by age class, dried, and separated into foliage and wood+bark. The samples were then re-dried for at least 24 hours and weighed (nearest 0.01 g).

Phase 2.—Immediately after the Phase 1 field work, 57 plots were measured more intensively to augment the data on tree and plot growth. During the summer of 1997, this subset of plots was revisited and all live Douglas-fir trees were measured for height to crown base and total height (ignoring the 1997 leader growth). Height growth trends of the two smallest trees felled in Phase 1 were reconstructed from branch whorls and bud scale scars as in Phase 1. An increment core was then removed from each standing Douglas-fir tree to estimate past annual radial growth. The side of the tree from which this core was extracted was defined by an imaginary line from plot center to the center of the tree at breast height. Increment cores were transported to the laboratory in paper drinking straws and measured for annual radial growth and sapwood radius (nearest 0.5 mm).

Phase 3.—A network of permanent plots was established in April 1998 at the locations previously sampled in Phases 1 and 2. These plots will be monitored continuously for height, diameter, and crown length of all conifers, and for various symptoms and indicators of SNC severity. The square plots are 0.08 ha (0.2 ac) in size and are centered on the fifth point of the ODF transect established in spring 1997 (Phase 1 plots were centered on the third point). This strategy provides several advantages over selection of entirely new locations: (1) some previous information on the status of Swiss needle cast at each plot center was available; (2) a significant cost saving was gained by not having to locate, map, and document a new set of plot locations; and (3) the sampled locations represented a standard list sample (pps sample) from the target population of Douglas-fir plantations, allowing future inferences to be extended to the population with statistical validity.

On each measurement plot, all trees were tagged at breast height and measured for total height, height to crown base, and dbh. Trees are scheduled for remeasurement every 2 years. SNC intensity was described for the 10 largest trees on each plot, considering both needle retention and chlorosis. A subset of these trees was cored to estimate sapwood area at breast height. SNC attributes will be collected on an annual basis.

Data Analysis

Patterns in past basal area and height growth were reconstructed from the annual height increments and stem section radial growth measurements. The tree and sample branch measurements from the plantation surveys and growth impact study allowed computation of many possible indices of SNC intensity. In an initial effort to gain some biological insight into the relationships among the various indices, a principal components analysis (Johnson and Wichern 1982) was performed.

Estimates of key stand-level variables for different annual growth periods required at least two assumptions: (1) no trees died from suppression mortality or were removed by thinning since the year in which the stands reached breast height; and (2) basal area growth of each species group was proportional to relative basal area growth of the sectioned and cored Douglas-fir trees on that plot. In addition to stand density measures for the total stand and for species groups, tree position variables were computed for each annual growth period, specifically expressed as the plot basal area in trees larger than the subject tree.

Height growth and basal area growth, the two major components of volume growth, were analyzed separately since it was evident early in the study that the onset of growth reductions in these two components were asynchronous and their relative magnitudes were different. The four largest trees on each plot were assumed to represent the site tree component of the stands. Site index was estimated yearly for each site tree by solving Bruce's (1981) equations iteratively for each height-age pair. An analysis of top height growth of the plots was implemented by computing potential predictor variables and subjecting the data to an all-subsets regression analysis with the logarithm of annual height growth as the response variable. In the final model, the "effect" of SNC was assessed by fitting the growth model on an annual basis, computing the percent of expected growth for extreme and moderate values of the included SNC index, and graphing this percent of expected growth from 1978 through 1996. In this approach, growth of plantations with the least severe SNC ratings serve as the expected growth rate, after correcting for the effects of other covariates in the regression model (that is, holding all other variables such as site quality and initial size constant).

Basal area growth data from all Douglas-fir measure trees, whether estimated from disks or cores, were combined in an all-subsets regression analyses to screen for the potentially most powerful predictor variables. The final model was fitted on a year-by-year basis, and the "effect" of SNC was depicted as the growth of trees across the range in the SNC index relative to those trees with the lowest apparent SNC intensity measured by the same SNC index.

CURRENT ASSESSMENT OF SNC

Aerial Survey

The aerial survey covered about 890,000 ha (2.2 million acres) of forest each year. The amount of area with obvious Swiss needle cast symptoms was 52,600 ha (130,000 ac) in 1996, 160,000 ha (395,000 ac) in 1997, and 70,000 ha (173,000 ac) in 1998 (Kanaskie and McWilliams 1998). Approximately 80 percent of the area with symptoms occurred north of Florence and the remaining portion occurred south of Florence. After 3 years of surveys, there is little doubt that Swiss needle cast symptoms continue to intensify. It is also clear that even though the disease occurs throughout the Coast Range, most areas with symptoms that can be detected from the air are within about 18 miles of the coast (fig. 1).

These estimates must be considered conservative because they represent only those areas with obvious symptoms. The aerial survey results do not depict the total extent and distribution of the disease, but only those areas where disease symptoms have developed enough to be visible from the air. Ground surveys indicated that Swiss needle cast occurred in all Douglas-fir stands throughout the survey area, but in many places symptoms were not developed enough to be detected by air. Factors other than the presence of the pathogen strongly affect disease development, and these factors remain poorly understood.

Plantation Surveys

Ground surveys revealed that many Douglas-fir stands within the survey area have SNC but were not mapped because they were not discolored enough to be visible from the air. Conversely, some mapped stands were found to be composed of predominantly western hemlock and were deleted from the GIS SNC layer. The average foliage retention for the target population of young plantations was 2.01 years. However, 67 percent of the area was estimated to have a foliage retention of 2 years or less, 22 percent to have foliage retention of 1.5 years or less, and 12 percent to have foliage retention of 1 year or less (fig. 2). Plots represented a range in stand density and tree size that is typical of Douglas-fir plantations in the Oregon Coast Range (table 1).

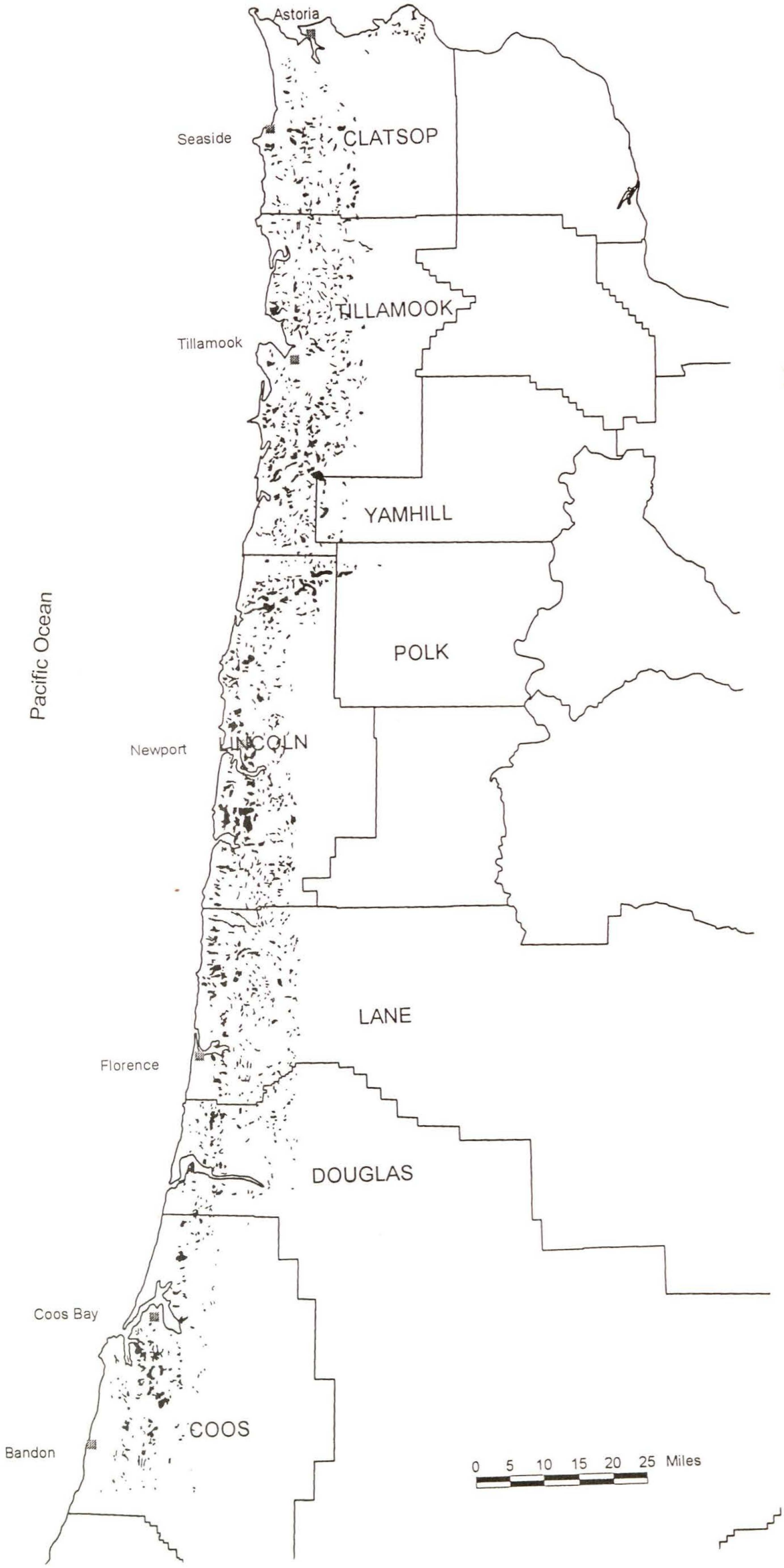

Astoria
Seaside
CLATSOP
TILLAMOOK
Tillamook
YAMHILL
POLK
Pacific Ocean
Newport
LINCOLN
LANE
Florence
DOUGLAS
Coos Bay
COOS
Bandon
0 5 10 15 20 25 Miles

Figure 1.—*Areas of Douglas-fir forest in Oregon Coast Range with SNC symptoms detected during an aerial survey in April-May 1998.*

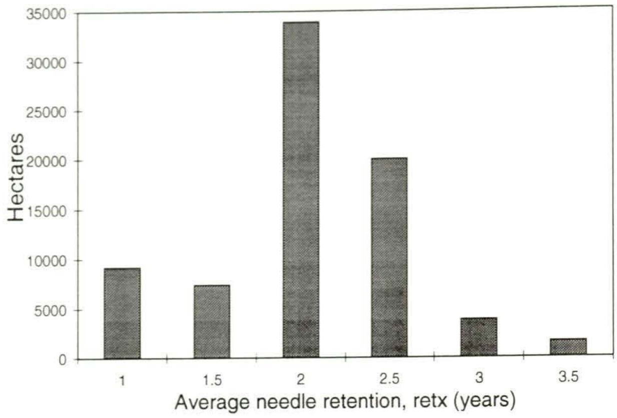


Figure 2.—*Estimated distribution of target population plantation area by SNC severity (indicated by average foliage retention in years).*

Table 1.—*Attributes of the 70 plots sampled in Phase 1 of the Growth Impact Study*

Attribute	Min	Mean	(sd)	Max
Total age	8	17	5.4	30
SI_{50}	23.40	39.25	4.62	47.20
TPH	247	1,627	2,223	17,142
TPD_{DF}	148	688	347	1,927
DQ	3.63	15.27	6.86	33.89
DQ_{DF}	5.52	17.81	6.63	3.56
BA	2.84	19.25	10.96	54.97
BA_{DF}	2.03	15.77	9.02	37.24
$BA_{CONIFERS}$	2.84	18.16	10.40	54.97
BA_{HD}	0	1.09	2.63	15.31
SDI	91	468	255	1,430
$SDI_{CONIFERS}$	91	427	235	1,430
RD	1.04	4.99	2.74	15.48
$RD_{CONIFERS}$	1.04	4.52	2.50	15.48

Growth Impact Study

Indices of SNC Infection Intensity

Principal components analysis of the SNC indices suggested that the data contained four or five functionally similar groups of variables. These groups include: (1) crown color/foliage retention; (2) fungal disruption of surviving foliage as indicated by fruiting body abundance; (3) foliage biomass age distribution / needle size; and (4) needle structure / foliage biomass amount. It is conceivable that foliage retention variables indicate effects of foliage loss in the growth analysis, while variables representing fungal density in foliage may signal direct physiological disruption of needle gas exchange. In other words, the various SNC indices should not necessarily be considered functionally equivalent or mutually exclusive.

Top Height Growth

The preliminary model for top height growth was selected to illustrate the relationship between degree of foliage retention and the trend in top height increment:

$$\ln(\Delta th) = c_0 + c_1 \bullet X_1 + c_2 \bullet \ln(retx) \qquad (1)$$

where $\ln(\bullet)$ = natural logarithm
Δth = annual top height growth (m/yr)
retx = average years of foliage retention
X_1 = Bruce's (1981) predicted top height growth
and c_0, c_1, and c_2 are regression parameters estimated from the data for each year of backdated height growth

In any given year this model accounted for 14 to 63 percent of the variation in top height growth. A significant correlation between foliage retention and top height growth emerged in 1992. The plantations implied to be most severely impacted by SNC according to impacts on foliage retention are growing at only 75 percent of the rate observed in "unaffected" plantations in 1996 (25 percent growth reduction; fig. 3). The top height growth trends prior to 1992 appear unrelated to the 1997 SNC ratings. Since 1992, however, a sustained reduction seems to have occurred in plantations rated with high SNC intensity, but this reduction was significant only in 1992 and 1996 (fig. 3). Given the average foliage retention of 2.01 years for the population, regionwide top height growth for these young plantations was approximately 90 percent of expected growth.

Basal Area Growth

The following preliminary model for tree basal area growth was based on an initial analysis of the Phase 1 data:

$$\ln(\Delta ba) = f_0 + f_1 \bullet \ln(idob) + f_2 \bullet BA + f_3 \bullet BAL + f_4 \bullet SI + f_5 \bullet retx \qquad (2)$$

where $\ln(\bullet)$ = natural logarithm
Δba = annual basal area growth of individual tree (cm^2/yr)
idob = tree DBH at start of growth period (cm)
BA = plot basal area (m^2/ha)

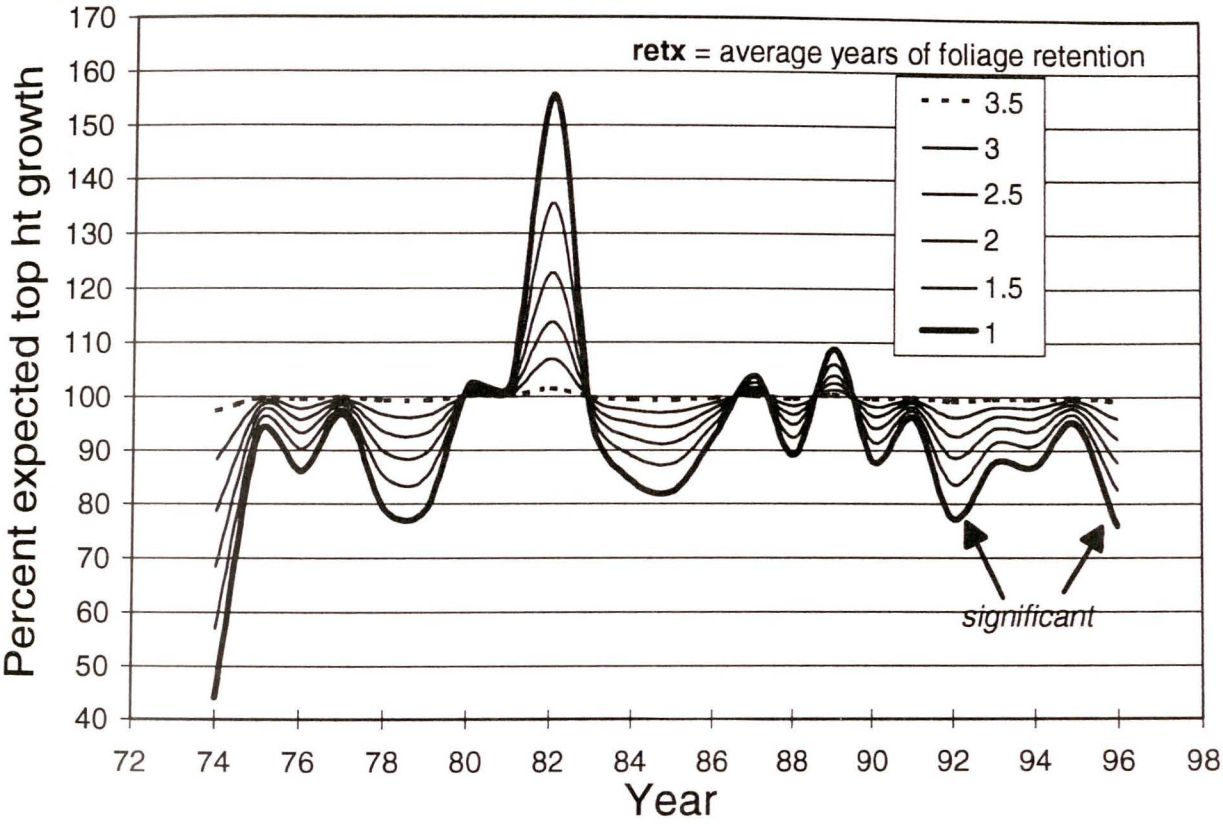


Figure 3.—*Trend in top height growth across the range in SNC severity (indicated by average foliage retention in years).*

BAL = basal area in trees with larger dbh than the subject tree (m^2/ha)
SI = Bruce's (1981) site index (m at 50 years)
retx = average years of foliage retention

and

f_0, f_1, f_2, f_3, f_4, and f_5 are regression parameters estimated from the data for each year

In any given year this model accounted for 53 to 97 percent of the variation in tree basal area growth. As expected, basal area growth declined with increasing BAL, increasing BA, and decreasing foliage retention (negative f_2 and f_3 and positive f_5). Plantations with a lower average age of foliage in 1997 started to slow in basal area growth around 1990 (fig. 4). In 1996, plantations with only a single age class of needles (retx=1) grew 65 percent of the growth expected for similar plantations with "normal" foliage retention (retx= 3-1/2 years). The mean foliage retention of 2.01 years implies a population basal area growth that is approximately 80 percent of the growth expected for young Douglas-fir plantations without SNC damage.

Regional Growth Losses

As mentioned above, the list sampling of the plantations meeting target population criteria yielded an average foliage retention of 2.01 years for the 75,929 ha (187,545 acres). Taking the associated values of 90 percent and 80 percent for the percentages of expected height and basal area growth, respectively, the corresponding volume growth in 1996 was approximately 72 percent of expected growth. This estimate suggests an average 28 percent growth loss in 1996 for the entire population. At the low extreme, plantations retaining only a single age class of needles were estimated to have experienced a 51 percent volume growth loss in 1996.

Most of these young plantations are not yet growing merchantable volume (for example, board feet). If expected volume growth (periodic annual increment) in slightly older stands averaged approximately 14 m^3/ha/yr (1,000 MBF/ac/yr), volume growth losses of 28 percent would translate into an annual growth loss of approximately 3.9 m^3/ha/yr (280 BF/ac). Expanding to the sampled population, growth loss in 1996 alone under this scenario would have been equivalent to approximately 297,000 m^3 (52.5 MMBF). It is important to recognize

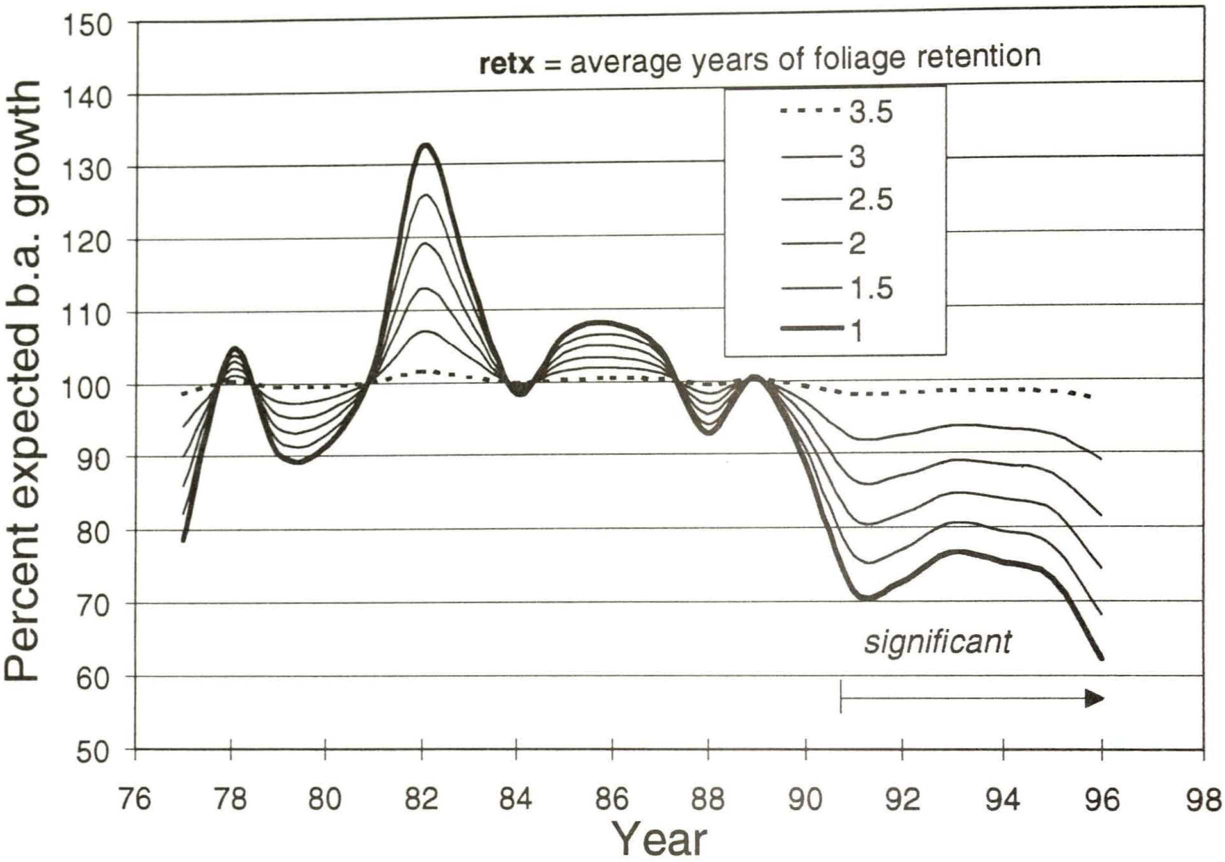


Figure 4.—*Trend in tree basal area growth across the range in SNC severity (indicated by average foliage retention in years).*

also that there is a large area of stands younger than 10 years and older than 30 years that are also affected by SNC and show growth reduction; hence, this is a conservative estimate of the regionwide growth loss from SNC damage.

SPECULATION ON DRIVING MECHANISMS

Several hypotheses have been suggested to explain why this normally benign pathogen is causing severe damage to Douglas-fir in its native range. Certainly the presence of the pathogen alone is not sufficient because the pathogen occurs on Douglas-fir everywhere in the Coast Range. The introduction or genesis of a highly virulent strain of the pathogen is a possible explanation, but preliminary research at Oregon State University (Everett Hansen, Jeff Stone, and Lori Winton) suggests that this is unlikely.

The more likely hypothesis is that our management practices, in combination with a climate that is conducive to the disease, have shifted the ecological balance in favor of the pathogen. Much of the Sitka spruce and western hemlock zones has been planted to dense stands of Douglas-fir. Many of these plantations were established from seed collected farther inland and at higher elevations than native coastal stands. The combination of a climate favorable for the disease, increase in the amount and density of Douglas-fir in coastal areas, and slightly off-site seed sources may have set the stage for rapid and efficient spread of the fungus. As a result, the pathogen population may have increased to levels that can overwhelm naturally occurring mechanisms of disease tolerance.

When Douglas-fir and the SNC pathogen are established beyond their natural geographic range, SNC consistently becomes severe and mitigation of damage is difficult and slow. Apparently a delicate balance exists between the tree, the pathogen, and the environment. Understanding the effects of various factors on this balance is critical for predicting long-term effects on forests and for formulating practical mitigation measures.

ACKNOWLEDGMENTS

This work was funded by the Swiss Needle Cast Cooperative, the Oregon Department of Forestry, and the USDA Forest Service Forest Health Monitoring program. Many individuals have contributed to the ideas, data, and analyses presented in this paper, particularly the foresters, scientists, and students involved in the Swiss Needle Cast Cooperative: Mark Gourley, John Washburn, Bill Voelker, Greg Johnson, Randy Johnson, Bill Atkinson, John Trobaugh, Greg Filip, Katy Kavanagh, Everett Hansen, Jeff Stone, Keith Sprengel, Jerry Beatty, Dave Overhulser, LeRoy Kline, Jack Prukop, Jim Baronek, Steve Dutton, Doug Mainwaring, Ryan Singleton, Minh Quoc Ho, Lou Beer, Chet Smith, Rick Christian, Dan Manter, Pablo Rosso, Lori Winton, Bryan Capitano, Wendy Sutton, Matthew Goslin, Laina Smith, Thomas VanDeusen, Nick Greiner, Connie Landis, Jerry Haan, and David Dyer. Field work for Phase 1 of the Growth Impact Study was completed by Miller Timber Services: Rick Allen, John Jayne, Arnold Schaffer, Clarence Stein, Consuello Brandis, Salvador Hernandez, Tim Miller, and Levi Miller. The initial field work for Phase 3 of the Growth Impact Study was done by Ted Reiss, Ed Malmsten, and Rick Barnes of Barnes & Associates, and Rick and Malia Allen of Woodland Planning & Management. Cooperating landowners for the north coast plantation surveys included Willamette Industries, Simpson Timber, Starker Forests, Stimson Lumber, Boise Cascade, The Timber Company (formerly Georgia-Pacific), Confederated Tribes of the Grande Ronde, Hampton Tree Farms, Miami Corporation, Longview Fiber, USDI Bureau of Land Management, USDA Forest Service, and the Oregon Department of Forestry.

The following people reviewed this paper: Greg Filip, Director, Swiss Needle Cast Cooperative, Department of Forest Science, Corvallis, OR, USA; and Randy Johnson, USDA Forest Service, Pacific Northwest Research Station, Corvallis, OR, USA.

LITERATURE CITED

Beekhuis, J. 1978. Growth decline in Douglas-fir. In: James, R.N.; Bunn, E.H., eds. A review of Douglas-fir in New Zealand. FRI Symposium No. 15. Rotorua, New Zealand: Forest Research Institute: 119-125.

Bruce, D. 1981. Consistent height-growth and growth-rate estimates for remeasured plots. Forest Science. 27: 711-725.

Forest Research Institute. 1978. Discussion on decline in growth. In: James, R.N.; Bunn, E.H., eds. A review of Douglas-fir in New Zealand. FRI Symposium No. 15. Rotorua, New Zealand: Forest Research Institute: 23-36.

Hansen, E.; Winton, L.; Cappitano, B. 1996. Swiss needle cast problem analysis: Why here? Why now? Unpublished report on file at Oregon Department of Forestry, Salem, OR.

Harrington, C.A.; Reukema, D.L. 1983. Initial shock and long-term stand development following thinning in a Douglas-fir plantation. Forest Science. 29: 33-46.

Hood, I.A.; Sandberg, C.J. 1979. Changes within tree crowns following thinning of young Douglas fir infected by Phaeocryptopus gaeumannii. New Zealand Journal of Forest Science. 9: 177-84.

Johnson, R.A.; Wichern, D.W. 1982. Applied multivariate statistical analysis. Englewood Cliffs, NJ: Prentice-Hall. 594 p.

Kanaskie, A.; McWilliams, M. 1998. Results of the 1998 Swiss needle cast aerial survey. Unpublished report. Salem, OR: Oregon Department of Forestry.

Kanaskie, A.M.; McWilliams, M.; Overhulser, D.; Kline, L. 1996. Aerial survey to monitor Swiss needle cast in coastal Oregon. Research proposal. Salem, OR: Oregon Department of Forestry.

Oregon Department of Forestry. 1998. Swiss needle cast of Douglas-fir in coastal western Oregon. Forest Health Note, March 1998. Salem, OR: Oregon Department of Forestry, Forest Health Program.

Oswald, D.D.; Hegyi, F.; Becker, A. 1986. The current status of coast Douglas-fir timber resources in Oregon, Washington, and British Columbia. Pp. 26-31 In: Oliver, C.D.; Hanley, D.P.; Johnson, J.A., eds. Douglas-fir: stand management for the future. Institute of Forest Resources Contribution No. 55. Seattle, WA: College of Forest Resources, University of Washington.

Russell, K.; Johnsey, R.; Edmonds, R. 1986. Disease and insect management for Douglas-fir. In: Oliver, C.D.; Hanley, D.P.; Johnson, J.A., eds. Douglas-fir: stand management for the future. Institute of Forest Resources Contribution No. 55. Seattle, WA: College of Forest Resources, University of Washington: 189-207.

USDA Forest Service. 1983. Swiss needle cast and rhabdocline needle cast. Forest Disease Management Notes. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 53 p.

The Urban Forest Effects (UFORE) Model: Quantifying Urban Forest Structure and Functions

David J. Nowak and Daniel E. Crane

Abstract.—The Urban Forest Effects (UFORE) computer model was developed to help managers and researchers quantify urban forest structure and functions. The model quantifies species composition and diversity, diameter distribution, tree density and health, leaf area, leaf biomass, and other structural characteristics; hourly volatile organic compound emissions (emissions that contribute to ozone formation) throughout a year; total carbon stored and net carbon sequestered annually; and hourly pollution removal by the urban forest and associated percent improvement in air quality throughout a year.

Few people know how many and what kind of trees are found in urban areas, or how these trees affect a city's environment and the health and well-being of its inhabitants. Measuring the urban forest is one of the first steps toward understanding this resource and developing appropriate management plans. Understanding and quantifying the impact of urban trees is an important prerequisite to managing city vegetation for optimal beneficial effects.

The Urban Forest Effects (UFORE) computer model was developed to help managers and researchers quantify urban forest structure and its functions. Written in SAS, the program incorporates vegetation data and local hourly meteorological and pollution-concentration measurements to quantify city-specific vegetation structure and functions. The model currently has four modules: (1) UFORE-A: Anatomy of the Urban Forest, which quantifies urban forest structure (e.g., species composition, tree density, tree health, leaf area, leaf biomass); (2) UFORE-B: Biogenic Volatile Organic Compound (VOC) Emissions, which quantifies hourly urban forest VOC emissions (emissions that contribute to ozone formation); (3) UFORE-C: Carbon Storage and Sequestration, which calculates total carbon stored and net carbon sequestered annually by urban trees; and (4) UFORE-D: Dry Deposition of Air Pollution, which quantifies hourly pollution removal by the urban forest and associated percent improvement in air quality. Pollution removal is calculated for ozone, sulfur dioxide, nitrogen dioxide, carbon monoxide, and particulate matter less than 10 microns. UFORE methods can be applied to areas of any size and to non-urban areas. Model results have been cross-checked and verified against test data sets and field measurements.

DATA REQUIREMENTS

Four types of data are needed to run all four UFORE modules: field, tree cover, meteorological, and pollution concentration data. Field data are collected within randomly located 0.04-ha plots throughout the study area, stratified by land-use type. Within each plot, data are collected on land use, ground and tree cover, shrub characteristics, and building features, as well as on individual-tree attributes of species, stem diameter at breast height (1.37 m), tree height, height to base of live crown, crown width, percent crown dieback, and distance and direction from buildings (to be used in a module under development: UFORE-E: Energy Effects on Buildings). Although tree cover measurements are made in the field, tree cover attributes often are also measured by sampling aerial photographs (Nowak *et al.* 1996).

Running the UFORE-B and D modules requires digital hourly meteorological data from the National Climatic Data Center (NCDC) (U.S. Department of Commerce 1970). UFORE-D also requires hourly pollution-concentration data from the U.S. Environmental Protection Agency's (EPA) Aerometric Information Retrieval System (AIRS database).

UFORE-A: ANATOMY OF THE URBAN FOREST

UFORE-A uses field data to quantify forest structure of an entire urban area, individual land uses, and/or of individual tree species. It quantifies total or means as well as standard errors (Cochran 1977) of number of trees, species composition, tree density, dbh and condition-class distribution, leaf area, and leaf biomass. This module also calculates species richness, Shannon-Wiener diversity index values, population distribution by region of origin (e.g., percent native species), and ground-cover type distribution. The proportions of leaf area and live tree population in various susceptibility classes to gypsy moth feeding (Liebhold *et al.* 1995) also are calculated to reveal an urban forest's susceptibility to gypsy moth defoliation.

Project Leader and Computer Specialist, respectively, USDA Forest Service, Northeastern Research Station, Syracuse, NY.

Leaf area and leaf biomass of individual trees are calculated using regression equations for deciduous urban trees (Nowak 1996). For deciduous trees whose size is beyond the appropriate input range for the regression equation (typically less than 10 percent of the population), leaf area is estimated using extrapolations of calculated leaf-area indices (LAI) for similar trees. For trees that are too large, average LAI is calculated by the regression equation for the maximum allowable tree size based on the appropriate height-width ratio and shading coefficient class of the tree. This calculated LAI is applied to the ground area covered by the crown of the specific tree to calculate its leaf area. For trees with height-to-width ratios that are too large or too small, tree height or width is scaled downward or upward to allow the crown to reach the maximum (2) or minimum (0.5) height-to-width ratio; the appropriate LAI for the maximum or minimum ratio is used to determine total leaf area. Leaf area is then scaled proportionally to obtain the original crown volume.

For all conifer trees, average LAI per height-to-width class for deciduous trees with a shading coefficient of 0.91 is applied to the tree's ground area to calculate leaf area. The 0.91 shading coefficient class is believed to be the best class to represent conifers because conifer forest LAI typically is about 1.5 times greater than deciduous forest stands (Barbour *et al.* 1980). The average shading coefficient for deciduous trees is 0.83 (Nowak 1996); 1.5 times the 0.83 class LAI is equivalent to the 0.91 class LAI.

Tree leaf biomass is calculated by converting leaf-area estimates using species-specific measurements from the literature (see Nowak 1994a) of g leaf dry weight per m^2 of leaf area. Shrub leaf biomass is calculated as the product of the crown volume occupied by leaves (m^3) as measured in the field and measured leaf biomass factors ($g\ m^{-3}$) for individual species (e.g., Nowak 1991, Winer *et al.* 1983). Shrub leaf area is calculated by converting leaf biomass to leaf area based on measured species conversion ratios ($m^2\ g^{-1}$). If there are no leaf biomass-to-area conversion factors or leaf biomass factors for an individual species, genera or hardwood/softwood averages are used. Estimates of leaf area and leaf biomass are adjusted downward based on percent crown dieback (tree condition).

Urban Forest Structure

The UFORE model has been used to quantify the urban forest structure in five cities (approximately 200 plots per city): Atlanta, GA, Baltimore, MD, Boston, MA, New York, NY, and Philadelphia, PA. Number of trees, tree cover, and tree density are highest in Atlanta (table 1). New York will be used to illustrate specific model results. The most common trees in New York are tree of heaven (*Ailanthus altissima*, 468,000 trees, 9 percent of total city tree population), black cherry (*Prunus serotina*, 424,000 trees, 8.1 percent), and sweetgum (*Liquidambar styraciflua*, 411,000 trees, 7.9 percent). Tree species that dominate the city in terms of leaf area are London planetree (*Platanus* x *acerifolia*, 14.3 percent of total city leaf area), sweetgum (10.1 percent), and northern red oak (*Quercus rubra*, 9.5 percent). These and other structural attributes are used to quantify various urban forest functions. An understanding of urban forest structure and how it impacts forest functions can lead to better urban forest management.

UFORE-B: BIOGENIC VOLATILE ORGANIC COMPOUND EMISSIONS

Trees emit volatile organic compounds (VOC's) that can contribute to the formation of ozone and carbon monoxide

Table 1.—*Estimates of number of trees and tree density (trees ha^{-1}) for cities analyzed with the UFORE model. Estimates of percent tree cover are based on satellite images or sampling of aerial photographs. Data from Oakland, CA (Nowak, 1991) and Chicago, IL (Nowak, 1994a) were not analyzed with UFORE (SE = standard error).*

City	Number of trees		Tree density		Tree cover (%)	
	Total	SE	Mean	SE	Mean	SE
Atlanta, GA	9,420,000	749,000	276	22	32.9	na
New York, NY	5,220,000	719,000	65	9	16.6	0.3
Chicago, IL	4,130,000	634,000	68	10	11.0	0.2
Baltimore, MD	2,600,000	406,000	109	17	18.9	na
Philadelphia, PA	2,110,000	211,000	62	6	21.6	0.4
Oakland, CA	1,590,000	51,000	120	4	21.0	0.2
Boston, MA	1,180,000	109,000	83	8	21.2	0.4

na = not analyzed; base data for Atlanta from American Forests; base data for Baltimore from Grove (1996).

(Brasseur and Chatfield 1991). The amount of emissions depends on tree species, leaf biomass, air temperature, and other environmental factors. UFORE-B estimates the hourly emission of isoprene, monoterpenes, and other volatile organic compounds (OVOC's) by species for each land use and for the entire city. Species leaf biomass (from UFORE-A) is multiplied by genera-specific emission factors (e.g., Benjamin *et al.* 1996, Geron *et al.* 1994) to produce emission levels standardized to 30°C and PAR flux of 1000 μmol m^{-2} s^{-1} (full sunlight). If genera- specific information is not available, median emission values for the family or order are used. Standardized emissions are converted to actual emissions based on light and temperature correction factors (Geron *et al.* 1994) and local meteorological data.

Urban Forest Influence on VOC Emissions

The species composition and leaf biomass of urban trees directly affect VOC emissions. Model results of planting of additional low VOC-emitting genera have been shown to decrease ozone concentrations in the Los Angeles Basin (Taha 1996). Shifting from high VOC-emitting genera may be another strategy to help improve air quality. High-emitting genera (emissions >35 μg g^{-1} leaf weight) include *Liquidambar* spp., *Quercus* spp., *Platanus* spp., *Populus* spp., *Rhamnus* spp., and *Salix* spp. The proportion of total tree leaf biomass in high-emitting genera was highest in New York (44.3 percent; 35,500 t leaf biomass in high-emitting genera), followed by Atlanta (29.7 percent; 27,900 t), Chicago (29.4 percent; 11,200 t), Baltimore (25.4 percent; 7,300 t); Boston (22.1 percent; 3,400 t), and Philadelphia (21.0 percent; 6,300 t). The three most dominant trees in New York (London planetree, northern red oak, and sweetgum) are high emitters and make up 35 percent of the city's total leaf biomass.

UFORE-C: CARBON STORAGE AND SEQUESTRATION

Carbon dioxide is a dominant greenhouse gas, and trees, through their growth process, sequester and store carbon (from carbon dioxide) in their tissue. Thus, trees are one potential means to help reduce atmospheric carbon dioxide. To calculate current carbon storage, biomass for each measured tree is calculated using allometric equations from the literature. If there is more than one equation, the mean of the biomass equation results is used. If there is no allometric equation for an individual species with a specific dbh and/or height, the average of results from appropriate equations of the same genera is used. If there are no genera equations, biomass is computed separately for each hardwood and conifer equation, and the average result from the hardwood or conifer group is used. For large trees (>97 cm dbh), volumetric equations from Hahn (1984) and specific gravity of wood are used to estimate biomass.

Biomass equations differ in what portion of tree biomass is calculated and in whether fresh or oven-dry weight is estimated. Equations that predict aboveground biomass are divided by 0.78 to convert to whole-tree biomass, as average belowground biomass of trees is approximately 22 percent of total tree biomass (see Nowak 1994b). Equations that compute fresh-weight biomass are multiplied by species- or genera- specific-conversion factors from the literature to yield dry-weight biomass. Open-grown, maintained trees tend to have less biomass than predicted by forest-derived biomass equations (Nowak 1994b). To adjust for this difference, biomass results for urban trees are multiplied by 0.8. No adjustment is made for trees found in more natural stand conditions (e.g., on vacant lands or in forest preserves). For dead and dying trees, leaf biomass is removed from the estimate of total tree biomass. Total tree and shrub dry-weight biomass is converted to total stored carbon by multiplying by 0.5 (e.g., Chow and Rolfe 1989).

Urban Tree Growth and Carbon Sequestration

To estimate the gross amount carbon sequestered annually, average diameter growth from the appropriate genera and diameter class is added to the existing tree diameter (year x) to estimate tree diameter in year $x+1$. For trees in forest stands, average dbh growth is estimated as 0.38 cm yr^{-1} (Smith and Shifley 1984); for trees in a park-like structure (e.g., parks, cemeteries, golf courses), average dbh growth is 0.61 cm yr^{-1} (deVries 1987); for more open-grown trees, dbh and genera specific growth rates, which average about 0.87 cm yr^{-1}, are used based on Nowak (1994b). Average height growth is calculated with formulas from Fleming (1988) and the specific dbh growth factor used for the tree. Growth rates are adjusted based on tree condition. For trees in excellent to fair condition (0-25 percent crown dieback), growth rates are multiplied by 1 (no adjustment). For trees with greater than 25 percent crown dieback, growth rates are adjusted downward based on percent dieback associated with the condition class. Dead tree growth rates are multiplied by 0. The difference in estimates of carbon storage between year x and year $x+1$ is the gross amount of carbon sequestered annually.

Carbon Storage and Sequestration in New York

Trees in New York City store approximately 1.2 million metric tons of carbon. This carbon, which took years to store, is equivalent to the amount emitted from New York's population in about 10 days based on average per capita carbon emissions (U.S. Dept. of Energy 1997). New York's trees sequester an estimated 39,000 t C yr^{-1}.

However, based on estimated mortality and tree removals (given New York's tree-condition distribution), net sequestration is likely negative due to carbon emissions from decomposition of dead and/or removed trees. New York City land uses that contain the most carbon in trees are open space (44 percent of total carbon stored by trees in the city), one- to two-family residential (28 percent), and vacant land (19 percent). Tree species that currently store the most carbon in New York are London planetree (13.6 percent of the total carbon stored), northern red oak (12.8 percent), and pin oak (*Quercus palustris*; 9.7 percent). Through proper planting strategies, urban trees also can reduce atmospheric carbon by reducing energy use in buildings and consequent emission of carbon dioxide from fossil fuel-based power plants. This avoidance of carbon emissions from power plants could be four times greater than direct carbon storage over the life of a mature tree (Nowak 1993).

UFORE-D: DRY DEPOSITION OF AIR POLLUTION

This module calculates the hourly dry deposition (i.e., pollution removal during nonprecipitation periods) of ozone (O_3), sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO), and daily deposition of particulate matter less than 10 microns (PM10) to tree canopies throughout the year. Pollutant flux (F) is calculated as the product of the deposition velocity (V_d) and the pollutant concentration (C):

$$F\ (g\ m^{-2}\ s^{-1}) = V_d\ (m\ s^{-1}) \times C\ (g\ m^{-3})$$

Deposition velocity is calculated as the inverse of the sum of the aerodynamic (R_a), quasi-laminar boundary layer (R_b) and canopy (R_c) resistances (Baldocchi *et al.* 1987):

$$V_d = (R_a + R_b + R_c)^{-1}$$

Specific procedures used to calculate R_a and R_b are given in Nowak *et al.* (1997). In-leaf, hourly tree-canopy resistances for O_3, SO_2, and NO_2 are calculated based on a hybrid of big-leaf and multi-layer canopy deposition models (Baldocchi *et al.* 1987, Baldocchi 1988). Hourly inputs to calculate canopy resistance are photosynthetic active radiation (PAR; $\mu E\ m^{-2}\ s^{-1}$), air temperature (K°), windspeed ($m\ s^{-1}$), u_* ($m\ s^{-1}$), carbon dioxide concentration (set to 360 ppm), and absolute humidity ($kg\ m^{-3}$). Air temperature, windspeed, u_*, and absolute humidity are measured directly or calculated from measured hourly meteorological data. Total solar radiation is calculated based on the National Renewable Energy Laboratory Meteorological / Statistical Solar Radiation Model (METSTAT) with inputs from the NCDC data set (Maxwell 1994). PAR is calculated as 46 percent of total solar radiation input (Monteith and Unsworth 1990).

Because the removal of carbon monoxide and particulate matter by vegetation is not directly related to transpiration, R_c for CO was set to a constant for in-leaf season (50,000 $s\ m^{-1}$) and leaf-off season (1,000,000 $s\ m^{-1}$) based on data from Bidwell and Fraser (1972). For particles, the deposition velocity (based on average V_d from the literature) was set at 0.0064 $m\ s^{-1}$ for the in-leaf season and 0.0014 $m\ s^{-1}$ for the leaf-off season, both of which incorporate a 50 percent resuspension rate of particles back to the atmosphere (Zinke 1967).

The model uses an urban tree LAI of 6, bark area index of 1.7, and a distribution of 90 percent deciduous and 10 percent coniferous leaf surface area (Nowak 1994a, Whittaker and Woodwell 1967). Local leaf-on and leaf-off dates are input into the model so that deciduous-tree transpiration and related pollution deposition are limited to the in-leaf period, and seasonal variation in removal can be illustrated for each pollutant. To limit deposition estimates to periods of dry deposition, deposition velocities were set to zero during periods of precipitation.

Hourly pollution-concentration data for gaseous pollutants (ppm) and average daily concentrations of PM10 ($\mu g\ m^{-3}$) are obtained from local EPA monitors. Hourly ppm values are converted to $\mu g\ m^{-3}$ based on measured atmospheric temperature and pressure (Seinfeld 1986). Missing hourly meteorological or pollution-concentration data are estimated using the monthly average for the specific hour. In a few locations, an entire month of pollution-concentration data may be missing and are estimated based on interpolations from existing data. For example, ozone concentrations may not be measured during winter months and existing O_3 concentration data are extrapolated to missing months based on the average national O_3 concentration monthly pattern.

Average hourly pollutant flux ($g\ m^{-2}$ of tree-canopy coverage) among the pollutant monitor sites is multiplied by city tree-canopy coverage (m^2) to estimate total hourly pollutant removal by trees across the city. Bounds of total tree removal of O_3, NO_2, SO_2, and PM10 are estimated using the typical range of published in-leaf dry deposition velocities (Lovett 1994). Monetary value of pollution removal by trees is estimated using the median externality values for the United States for each pollutant. The externality values are: NO_2 = \$6,750 t^{-1}, PM10 = \$4,500 t^{-1}, SO_2 = \$1,650 t^{-1}, and CO = \$950 t^{-1} (Murray *et al.* 1994). Externality values for O_3 were set to equal the value for NO_2.

To approximate boundary-layer heights in the study area, local daily morning and afternoon mixing heights are obtained and interpolated to produce hourly values using the EPA's PCRAMMIT program (U.S. EPA 1995). Minimum boundary-layer heights are set to 150 m during the night and 250 m during the day based on estimated minimum boundary-layer heights in cities. Hourly mixing heights (m) are used in conjunction with pollution concentrations (µg m^{-3}) to calculate the amount of pollution within the mixing layer (µg m^{-2}). This extrapolation from ground-layer concentration to total pollution within the boundary layer assumes a well-mixed boundary layer, which is common during the daytime (unstable atmosphere) (e.g., Colbeck and Harrison 1985). The amount of pollution in the air is contrasted with the amount of pollution removed by trees to calculate the relative effect of trees in reducing local pollution concentrations:

$$E = R\,(R+A)^{-1}$$

where E = relative reduction effect (%); R = amount removed by trees (kg); A = amount of pollution in the atmosphere (kg).

Air Pollution Removal by Urban Trees

In 1994, trees in New York City removed an estimated 1,821 metric tons of air pollution at an estimated value to society of $9.5 million (table 2). Air pollution removal by urban forests in New York was greater than in Atlanta and Baltimore (table 2), but pollution removal per m^2 of canopy cover was fairly similar among these cities (New York: 13.7 g m^{-2} yr^{-1}; Baltimore: 12.2 g m^{-2} yr^{-1}; Atlanta: 10.6 g m^{-2} yr^{-1}). These standardized pollution removal rates differ among cities according to the amount of air pollution, length of in-leaf season, precipitation, and other meteorological variables.

Air quality improvement in New York due to pollution removal by trees during daytime of the in-leaf season averaged 0.47 percent for PM10, 0.45 percent for O_3, 0.43 percent for SO_2, 0.30 percent for NO_2, and 0.002 percent for CO. Air quality improves with increased percent tree cover and decreased boundary-layer heights. In urban areas with 100 percent tree cover (i.e., contiguous forest stands), short-term improvements in air quality (one hour) from pollution removal by trees were as high as 15 percent for O_3, 14 percent for SO_2, 13 percent for PM10, 8 percent for NO_2, and 0.05 percent for CO.

CONCLUSION

The UFORE model and data-collection methodology provide a relatively easy and low-cost means of assessing and quantifying urban forest structure and functions in cities across the United States. The resulting data will aid urban forest managers in understanding their resource and developing management plans and vegetation designs to increase human and environmental health and well-being.

Table 2.—*Total estimated pollution removal (metric tons) by trees during nonprecipitation periods (dry deposition) and associated monetary value (thousand dollars) for New York (800 km^2), Atlanta (341 km^2), and Baltimore (209 km^2) in 1994. Estimates are for ozone (O_3), particulate matter less than 10 microns (PM10), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), and carbon monoxide (CO). Numbers in parentheses represent expected range of values (no range determined for CO). Monetary value of pollution removal by trees was estimated using the median externality values for United States for each pollutant (Murray* et al. *1994). Externality values for O_3 were set to equal the value for NO_2.*

	New York, NY		Atlanta, GA		Baltimore, MD	
Pollutant	Removal	Value	Removal	Value	Removal	Value
O_3	506	3,417	514[1]	3,471[1]	180	1,214
	(124-631)	(839-4,263)	(101-604)	(684-4,081)	(42-221)	(284-1,494)
PM10[2]	470	2,120	406	1,833	137	618
	(182-834)	(819-3,761)	(157-706)	(709-3,184)	(53-239)	(239-1,079)
NO_2	510	3,441	145	979	115	733
	(216-593)	(1,459-4,004)	(72-165)	(483-1,115)	(48-134)	(322-907)
SO_2	238	394	95	158	55	91
	(117-358)	(193-593)	(42-137)	(69-227)	(26-85)	(42-140)
CO	97	93	35	33	13	12
Total	1,7821	9,465	1,196	6,474	499	2,709
	(736-2,514)	(3,404-12,713)	(407-1,648)	(1,979-8,640)	(181-692)	(900-3,632)

[1] Average national O_3 monthly trend data were used to estimate missing data for January, February, and December.

[2] Assumes 50 percent resuspension of particles.

ACKNOWLEDGMENTS

The authors thank Myriam Ibarra, Patrick McHale, and Jack Stevens for assistance in model development; Chris Luley for assistance with field-data collection; and the following people who reviewed this manuscript: Andrew Kenney, University of Toronto, Toronto, Ontario, Canada; and Jan Thompson, Iowa State University, Ames, Iowa, USA.

LITERATURE CITED

Baldocchi, D. 1988. A multi-layer model for estimating sulfur dioxide deposition to a deciduous oak forest canopy. Atmosphere Environment. 22: 869-884.

Baldocchi, D.D.; Hicks, B.B.; Camara, P. 1987. A canopy stomatal resistance model for gaseous deposition to vegetated surfaces. Atmosphere Environment. 21: 91-101.

Barbour, M.G.; Burk, J.H.; Pitts, W.D. 1980. Terrestrial plant ecology. Menlo Park, CA: Benjamin/Cummings Publication Co. 604 p.

Benjamin, M.T.; Sudol, M.; Bloch, L.; Winer, A.M. 1996. Low-emitting urban forests: a taxonomic methodology for assigning isoprene and monoterpene emission rates. Atmosphere Environment. 30(9): 1437-1452.

Bidwell, R.G.S.; Fraser, D.E. 1972. Carbon monoxide uptake and metabolism by leaves. Canadian Journal of Botany. 50: 1435-1439.

Brasseur, G.P.; Chatfield, R.B. 1991. The fate of biogenic trace gases in the atmosphere. In: Sharkey, T.D.; Holland, E.A.; Mooney, H.A., eds. Trace gas emissions by plants. New York: Academic Press: 1-27.

Chow, P.; Rolfe, G.L. 1989. Carbon and hydrogen contents of short-rotation biomass of five hardwood species. Wood and Fiber Science. 21(1): 30-36.

Cochran, W.G. 1977. Sampling methods. New York: John Wiley and Sons. 428 p.

Colbeck, I.; Harrison, R.M. 1985. Dry deposition of ozone: some measurements of deposition velocity and of vertical profiles to 100 metres. Atmosphere Environment. 19(11): 1807-1818.

deVries, R.E. 1987. A preliminary investigation of the growth and longevity of trees in Central Park. New Brunswick, NJ: Rutgers University. 95 p. M.S. thesis.

Fleming, L.E. 1988. Growth estimation of street trees in central New Jersey. New Brunswick, NJ: Rutgers University. 143 p. M.S. thesis.

Geron, C.D.; Guenther, A.B.; Pierce, T.E. 1994. An improved model for estimating emissions of volatile organic compounds from forests in the eastern United States. Journal of Geophysical Research. 99(D6): 12,773-12,791.

Grove, J.M. 1996. The relationship between patterns and processes of social stratification and vegetation of an urban-rural watershed. New Haven, CT: Yale University. Ph.D. dissertation.

Hahn, J.T. 1984. Tree volume and biomass equations for the Lake States. Res. Pap. NC-250. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 10 p.

Liebhold, A.M.; Gottschalk, K.W.; Muzika, R.; Montgomery, M.E.; Young, R.; O'Day, K.; Kelley, B. 1995. Suitability of North American tree species to the gypsy moth: a summary of field and laboratory tests. Gen. Tech. Rep. NE-211. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station. 34 p.

Lovett, G.M. 1994. Atmospheric deposition of nutrients and pollutants in North America: an ecological perspective. Ecological Application. 4: 629-650.

Maxwell, E.L. 1994. A meteorological/statistical solar radiation model. In: Proceedings of the 1994 annual conference of the American solar energy society. San Jose, CA: American Solar Energy Society: 421-426.

Monteith, J.L.; Unsworth, M.H. 1990. Principles of environmental physics. New York: Edward Arnold.

Murray, F.J.; Marsh, L.; Bradford, P.A. 1994. New York State energy plan, Vol. II: issue reports. Albany, NY: New York State Energy Office.

Nowak, D.J. 1991. Urban forest development and structure: analysis of Oakland, California. Berkeley, CA: University of California. 232 p. Ph.D. dissertation.

Nowak, D.J. 1993. Atmospheric carbon reduction by urban trees. Journal of Environmental Management. 37: 207-217.

Nowak, D.J. 1994a. Urban forest structure: the state of Chicago's urban forest. In: McPherson, E.G.; Nowak, D.J.; Rowntree, R.A., eds. Chicago's urban forest ecosystem: results of the Chicago Urban Forest Climate Project. Gen. Tech. Rep. NE-186. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 3-18; 140-164.

Nowak, D.J. 1994b. Atmospheric carbon dioxide reduction by Chicago's urban forest. In: McPherson, E.G.; Nowak, D.J.; Rowntree, R.A., eds. Chicago's urban forest ecosystem: results of the Chicago Urban Forest Climate Project. Gen. Tech. Rep. NE-186. Radnor, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station: 83-94.

Nowak, D.J. 1996. Estimating leaf area and leaf biomass of open-grown deciduous urban trees. Forest Science. 42(4): 504-507.

Nowak, D.J.; McHale, P.J.; Ibarra, M.; Crane, D.; Stevens, J.; Luley, C. 1997. Modeling the effects of urban vegetation on air pollution. In: Proceedings of the 22nd NATO/CCMS international technical meeting on air pollution and its application. Clermont-Ferrand, France: Imprimerie des UFR Sciences: 276-283.

Nowak, D.J.; Rowntree, R.A.; McPherson, E.G.; Sisinni, S.M.; Kerkmann, E.; Stevens, J.C. 1996. Measuring and analyzing urban tree cover. Lands. Urban Planning. 36: 49-57.

Seinfeld, J.H. 1986. Atmospheric chemistry and physics of air pollution. New York: John Wiley and Sons. 738 p.

Smith, W.B.; Shifley, S.R. 1984. Diameter growth, survival, and volume estimates for trees in Indiana and Illinois. Res. Pap. NC-257. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 10 p.

Taha, H. 1996. Modeling impacts of increased urban vegetation on ozone air quality in the South Coast Air Basin. Atmosphereic Environment. 30(20): 3423-3430.

U.S. Department of Commerce. 1970. National Climatic Data Center WBAN Hourly Surface Observations TD-1440 Documentation Manual. Asheville, NC: National Oceanic and Atmospheric Administration. 14 p.

U.S. Department of Energy, Energy Information Administration. 1997. Emissions of greenhouse gases in the United States 1996. Washington, DC: U.S. Department of Energy, Energy Information Administration.

U.S. Environmental Protection Agency. 1995. PCRAMMIT user's guide. Research Triangle Park, NC: U.S. Environmental Protection Agency.

Whittaker, R.H.; Woodwell, G.M. 1967. Surface area relations of woody plants and forest communities. American Journal of Botany. 54: 931-939.

Winer, A.M.; Fitz, D.R.; Miller, P.R.; Atkinson, R.; Brown, D.E.; Carter, W.P.; Dodd, M.C.; Johnson, C.W.; Myers, M.A.; Neisess, K.R.; Poe, M.P.; Stephens, E.R. 1983. Investigation of the role of natural hydrocarbons in photochemical smog formation in California. Riverside, CA: Statewide Air Pollution Research Center. 234 p.

Zinke, P.J. 1967. Forest interception studies in the United States. In: Sopper, W.E.; Lull, H.W., eds. Forest hydrology. Oxford, UK: Pergamon Press: 137-161.

Using Widely Spaced Observations of Land Use, Forest Attributes, and Intrusions to Map Resource Potential and Human Impact Probability

Victor A. Rudis

Abstract.—Scant information exists about the spatial extent of human impact on forest resource supplies, i.e., depreciative and nonforest uses. I used observations of ground-sampled land use and intrusions on forest land to map the probability of resource use and human impact for broad areas. Data came from a seven-state survey region (Alabama, Arkansas, Louisiana, Mississippi, east Oklahoma, Tennessee, and east Texas) containing 32,000 land-use plots, with detailed attribute information for about half of these plots classed as forest land. Forest land attributes included human-associated intrusions (beverage containers, garbage, livestock grazing, timber management activities), proximity to nonforest land, forest fragment size, ownership, and forest type. Tools included geographic information software, a 100 MHz Pentium I processor, and 0.4-ha land-use and forest resource sample plots nominally spaced at 4.8-km intervals. I transferred information from sample plot locations to grid cells sized large enough to minimize computer memory storage and computation requirements, and small enough to conservatively model information from adjacent cells with plot information and include no more than one sample plot per cell. Results used spatially moving averages, with examples, to assess the spatial context of forest resources. Maps displayed regions of high and low probability of altered forest resources, forest attributes, and patterns qualitatively correlated with nonforest land-use neighborhoods. Findings suggested land areas with potential for multiple resource uses and forest land vulnerable to nonforest conversion.

Regional resource inventories (e.g., the USDA Forest Service's Forest Inventory and Analysis [FIA] and the Natural Resources Conservation Service's National Resources Inventory [NRI] program) document the status and change in land use and resource production from widely spaced observations at ground-sampled locations. Limited spatial information exists about the extent and potential for human impact, i.e., depreciative and multiple uses, on resource supplies. These inventory findings traditionally provide tabular statistics and note attribute locations spatially by political subdivision, e.g., by state and county. I conducted a study to (1) document an approach to more uniformly illustrate spatial relationships of inventoried attributes from widely spaced ground observations, and (2) make an initial, coarse-scale evaluation of the extent and probability of regional resource potential from observations of human intrusions. Examples that follow use land-use surveys, forest resource inventories, and ground observations, but the methods of this study could be applied to most other systematically sampled, widely spaced earth surface surveys.

Ground-based regional forest resource inventory sample plots in the United States, which range in size from 0.1 to 8 ha, are generally too small or otherwise an inadequate sample for quantifying resources other than forest vegetation, such as wildlife populations and recreation opportunities. Resources requiring larger samples must be aggregated to larger land divisions. Sample information aggregated by county, for example, yields estimates of black bear habitat and primitive-oriented recreation opportunities (Rudis and Tansey 1995). Although aggregation by county or other administrative division in inventory planning is often straightforward, natural resources and the processes that affect them may not be aligned with those divisions. An intuitively appealing approach is to aggregate information with a uniform-sized, large-area division, or "window," that encompasses several sample plots. Incorporating the context (location, adjacency, and neighborhood) with spatially referenced sample plot locations entails calculating spatially moving averages, i.e., moving the window across the earth surface so that the average at any location always depends on the nearest plot values. "Neighborhoods" are broad regions with similar attributes or values.

Of particular interest are forest resources adjacent to nonforest uses or in nonforest neighborhoods named by their predominant land use. Forest land in urban and built-up land neighborhoods or adjacent to roads may yield lower forest land estimates than estimates that ignore these contexts (Befort *et al.* 1988). Forest land near urban areas has reduced timber harvests (Barlow *et al.* 1998) and primitive-oriented recreation opportunities (Rudis 1987). In regions of high human population

---

Research Forester, Forest Inventory and Analysis Unit, Southern Research Station, U.S. Department of Agriculture, Forest Service, Starkville, MS 39760-0928, USA.

density, forest plots are associated with smaller forest fragments—which suggests lower logging profitability, fewer forest-interior wildlife species, and diminished primitive forest recreation opportunities (Rudis 1998). Forest land in agriculture-dominated regions may represent a temporarily fallow field or shade for livestock as much as it represents a potential supply of timber products.

In this paper, I focused on questions such as "Where do beverage containers, garbage dumping and livestock grazing occur in forests?" "Why are they located there?" "Where are the most and least fragmented forests?" "Is the concentration of forest plantations in the South widespread, composed only of loblolly pine forests, and exclusively concentrated in forest-industry-held areas of the region?" Answers provided geographic descriptions and fueled generation of hypotheses about regions with affected timber supplies, resource problem areas, and novel multiple-resource production opportunities.

METHODS

Data came from U.S. Department of Agriculture, Forest Service, Forest Inventory and Analysis (FIA) surveys conducted between 1988 and 1995 for Alabama, Arkansas, Louisiana, Mississippi, east Oklahoma, Tennessee, and east Texas. FIA sampled land use systematically and estimated approximate latitude and longitude for 32,000 0.4-ha sample plots spaced at 4.8-km intervals. They obtained more detailed attribute information on about 17,000 plots classed as forest land.

Kriging, variography, conditional analysis, and associated geostatistics make up a suite of analytical methods for estimating the spatial dependence of sample plots, spatially averaging plot attributes across different directions of a land surface, selecting weights for distant samples, and assessing the likelihood of patterns obtained (Deutsch and Journel 1998, Isaaks and Srivastava 1989). Hershey (1996) noted that kriging is "not extremely time-consuming nor difficult to process." However, such approaches are computationally intensive for large data sets and require considerable online memory capacity. Converting sample plot values to cover probabilities and averaging these values uniformly along a land surface is a coarse, but readily straightforward, geostatistical approach for exploratory analysis. This spatially moving average approach is particularly appealing with restricted memory capacity and limited geostatistical software. Attributes are spatially autocorrelated (associated with other samples in close proximity) when predicted from their context. Examination and hypothesis formation follow in three steps: (1) map the data in a land coordinate system, (2) choose the appropriate grain size, and (3) illustrate the mean probability for the attributes of interest and suggest potential causes for patterns obtained. Further assessments would then estimate resource statistics, such as area and volume, by regions having similar attribute probabilities.

For this initial exploratory effort, I first converted FIA sample plot locations to grid cells, calculated spatially moving averages, and then examined patterns. FIA used the intersection of 4.8-km lines aligned on county maps in cardinal directions to establish plots. FIA based plot locations on these lines, in latitude and longitude, yielding accuracy better than ±0.8 km (Dennis Jacobs, personal communication). I transferred sample attribute information to 2.4-km grid cells oriented in cardinal directions to limit computations. At the 2.4-km grid-cell size, the dimension was "small enough to define the most detailed geographic feature" (ESRI 1996b), yet large enough to minimize computer memory storage space and software calculations. The transfer to 2.4-km grid cells nominally assigned one grid cell per south central United States FIA sample plot, even at county borders. The grid-cell dimension—about half the size of the approximate space between sample plots—permitted a conservative interpolation from adjacent grid cells with sample plot attribute information.

Spatially moving averages used here were estimates within a circle of a given radius. The spatially moving averages for land use estimated the probability of forest and nonforest cover for each grid cell with sample plot attribute information. The grain size was the radius of the circle used to calculate spatially moving averages. A grain size of 4.8-km radius (approximately 7,240 ha) encompassed about 13 grid cells—up to 5 of which were FIA sample plots. This yielded an occurrence probability of 0, 1, 2, 3, 4, or 5, out of 5 samples. Only grid cells associated with sample plots contributed to averages.

Because single resource surveys commonly note attributes only on land areas of interest, the likelihood of sampling the attributes varies with land use. Table 1 lists expected values at selected grain sizes for south central FIA data. For small grain sizes, estimates are most reliable in uniform land-use regions. In many cases, a fine grain size limits interpretability, because sample size is low and random patterns obscure broader patterns. A grain size with a 24-km radius represents about 181,000 ha, 49 FIA land-use samples, or 25 forest attribute samples (if 50 percent forested). This grain size may be most appropriate for county and regional assessments, but contains fewer of the details needed for township and city planning.

I used location information from sampled plots to model occurrence probability by interpolation. Indicator maps suggested locations with high or low probability of categorical attributes. Interval maps suggested locations with high or low values of a continuous attribute, e.g.,

Table 1.—*Radius, area, and expected number of samples to calculate spatially moving average values, Forest Inventory and Analysis surveys of the south central United States*

Radius (English units)	Land area (English units) represented by the mean	Nominal number of land-use plots	Nominal number of forested plots (if 50 percent forested)
2.4 km (1.5 mi)	1,810 ha (4,470 ac)	0.5	0.3
4.8 km (3.0 mi)	7,240 ha (17,900 ac)	5	3
9.6 km (6.0 mi)	28,900 ha (71,500 ac)	13	7
24.0 km (15.0 mi)	181,000 ha (447,000 ac)	49	25
48.0 km (30.0 mi)	723,000 ha (1,790,000 ac)	109	55

forest fragment size. Interpolation of the means was straightforward, i.e., the technique assumed that the attribute probability (or attribute value) varied continuously and uniformly across the sampled region.

I employed the circular neighborhood mean statistics function within ArcView 3.0a geographic information software with the Spatial Analyst extension (ESRI, Inc. 1996b). Calculation of means provided averages beyond the range of the sampled region—a scenario in classic statistics comparable to drawing a regression line beyond the range of the data. To mask these areas, I created a data layer of grid cells with 20 percent or less forest land probability, based on a 4.8-km radius grain size and averaged from land-use sample plots. For south central FIA surveys of forest attributes, the mask included grid cells with no forests (extensive areas of nonforest land in the Mississippi Alluvial Plain) and extensive areas with no FIA plot samples (nonsurveyed locations and largely nonforested counties in western Oklahoma, western Texas, and extreme south Louisiana).

Estimation occurred in three stages, following a specific protocol: (1) define, record, and import into the software the attributes tied to objectives of interest; (2) generate land-use probability maps; (3) generate forest attribute maps. Due to space limitations, I have illustrated only a few of the attributes in this report. Rudis *(in press)* illustrated others that were likely spatially autocorrelated, such as hunting, restrictive signs (hunting restricted, no trespass, or keep out), timber management (harvest, site preparation, plantation establishment), tree and forest composition, site productivity, damage agents, and nonforest land-use proximity.

Samples were of 0.4-ha earth cover at the intersection of 4.8-km lines in cardinal directions established county by county in the south central states. FIA collected detailed information on forest land—0.4 ha and larger, ≥37 m in width, and not developed for nonforest uses. I selected a few of the many FIA attributes listed in the field manual (FIA Staff 1994) as examples to illustrate spatial relationships. These were: (1) Human-associated litter—presence or absence of beverage containers, or apparent garbage dumps within a 0.4-ha sample area. The purpose was to note prior use and accessible areas for urban recreation opportunities (e.g., picnicking), and degraded recreational values for primitive recreation opportunities (e.g., hunting, wilderness hiking). In forests, if the majority of beverage containers formerly contained alcoholic beverages—as was true along roadsides (Dennis Brezina, Aluminum Anonymous, Chesapeake City, MD, personal communication, 1998)—then they also suggested locations with potential safety hazards. (2) Livestock grazing—presence of cattle, dung, trails, or livestock tracks on the 0.4-ha plot, which suggested recent livestock grazing. The purpose was to note areas without exclusive timber production, with potentially degraded forest resources, or with agroforest (silvopastoral) management. (3) Forest fragment size classæcontiguous forest area class associated with a 0.4-ha sample plot. "Contiguous" forest meant unbroken by water or nonforest cover ≥37 m wide and determined from 1:58,000 scale high-altitude color aerial photographs. Classes were 0.4 to 4.0 ha (midpoint 2 km), 5 to 20 (12), 21 to 40 (30), 41 to 202 (121), 203 to 1,012 (607), 1,013 to 2,023 (1,518), and >2,023 (set at 3,323 ha). Although one fragment could be large enough to be associated with more than one sample plot, every plot was assumed to be a different fragment. The purpose was to estimate forest land with economic harvest potential, primitive recreation opportunities, and habitats for wildlife in need of seclusion (black bear) or large expanses of forest land (Cerulean warbler). (4) Selected timber management activities: forest plantations, forest industry ownership, and forest type of the 0.4-ha plot, as described in field manuals (FIA Staff 1994).

To generate land-use and forest attribute maps from ground information, I opted to convert FIA plot latitude and longitude estimates (accuracy better than 0.8 km) to Albers equal-area projection. I used ArcView 3.0a with the Spatial Analyst extension (ESRI, Inc. 1996b) on a personal computer with a Microsoft Windows 95 operating system, a 100MHz Pentium I processor, and 144 MB of Random Access Memory (RAM). The added RAM was to help speed the processing of input and output of the large seven-state FIA data set (32,000 records). If using GIS software other than ArcView 3.0a and Spatial Analyst 1.1, note that the order of steps below may vary. If using another data set, adapt the procedures noted in parentheses that are specific to south central U.S. FIA data.

Land-Use Maps

1. Obtain location of plot sample land-use estimates (0.4-ha plots sampled at 4.8-km intervals). 2. Convert plot sample locations to an ArcView grid at one-half the spacing (2.4-km cells). 3. Reclassify ArcView grid cells with land-use estimates as binary (0=nonforest, 1=forest), and estimate the mean value probability by averaging across an area with multiple samples. (A radius that encompassed up to five south central FIA samples used a 4.8-km radius, yielding probabilities of 0, 20, 40, 60, 80, or 100 percent.)

Forest Attributes

1. Obtain location of plot sample attribute estimates within the land use of interest. 2. Convert plot sample locations to an ArcView grid at one-half the spacing (2.4-km cells). 3. Reclassify ArcView grid cells: 3a. If an indicator attribute, reclassify as a binary variable ("0"=forest without attribute, "1"=forest with attribute), and estimate mean probability, in percent. 3b. If an interval attribute (e.g., forest fragment size class), determine whether attribute values are normally distributed, and if so, transform them as needed. (Forest fragment size class is best represented as log[midpoint of forest fragment size class.]) Generally, attribute estimates outside the land use of interest are classed "no data." 4. Estimate the mean (a) percentage or (b) value, by averaging across an area with multiple samples at a grain-cell size appropriate to the objective and sampling density. (For FIA forest attributes, a 9.6-km radius encompassed 7 to 13 samples, and a radius of 24 km encompassed about 25 to 49 samples [see table 1]). 5. Remove or "mask" from the map all land uses not sampled or not of interest. (For forest land attributes, use estimates with an 80 percent probability [from land-use map estimation]that the locations were nonforest).

RESULTS AND DISCUSSION

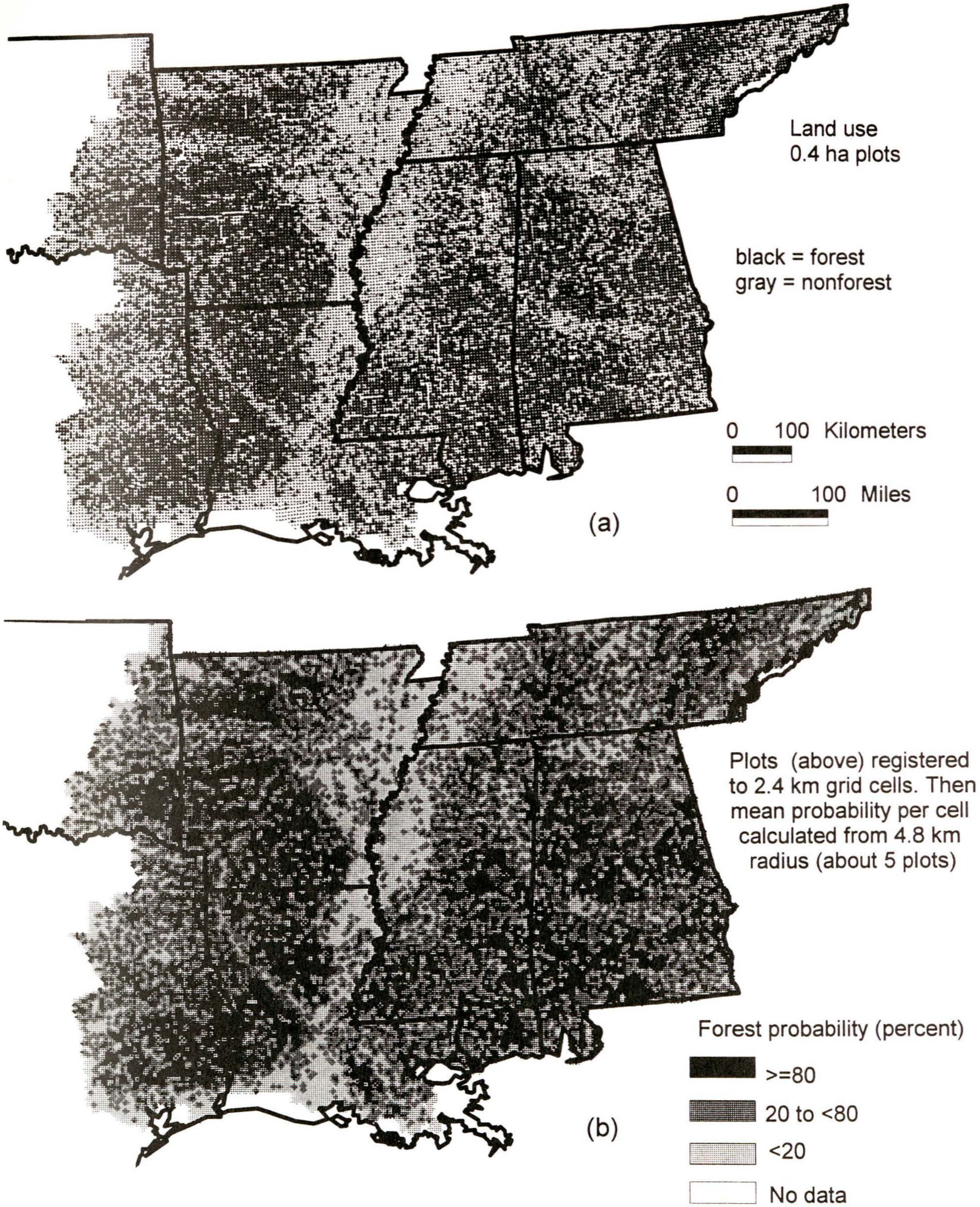
Illustrated by sample plot location and by forest land probability are forest and nonforest land use (fig. 1). Forest land probability came from forest occurrence averaged over a 7,240-ha area encompassed by a radius of 4.8 km, which incorporated about five land-use plots. The spatially moving average assumed uniform probability of forest land. In the real world, however, forest land is more frequent along the direction of, and close to, water courses, on steep terrain, and associated with particular soils and climate patterns. The simplified ground sample-based averaging procedures used in this report ignored them. More detailed geostatistical analyses by ecoregion or physiography, testing of hypotheses, and relaxation of isotropic forest probability assumptions are needed to quantify uncertainty. Because FIA located the sample plots on a regular grid, I made no extensive examination of alternative grain sizes. In this case, and in others with a random array of sample locations, results were likely indicative, but not definitive, because representations of forest area (and forest attribute data described below) at other grain sizes could lead to other conclusions.

At the 9.6-km radius, depicting averages of attributes collected only on forest land held greater uncertainty. This grain size provided estimates of more heuristic value, because averages included very few sample observations. Figure 2 illustrates both the sample value locations and the averages for beverage container occurrence in forests. Among prominent areas of high probability was a broad area along the very few forests of the Mississippi Delta in eastern Arkansas, the White River and Interstate 40 rest stop between Little Rock, AR, and Memphis, TN.

Resulting patterns varied with changes in grain size. I used a 9.6-km radius as a minimum, a 48-km maximum, an intermediate radius of 24 km, and beverage containers in forested areas as an example (fig. 3). In these three depictions, the universal conclusion from FIA data was that the Mississippi Delta in eastern Arkansas had a larger concentration of forests with beverage containers, on average, than other areas. I settled on the 24-km radius for subsequent analyses, because the 24-km radius grain size yielded lower uncertainty (averages based on about 25 forested plots). The 24-km radius grain size also approximated the size of a county planning area, or portion of a large city, which the larger grain size obscured.

Human Impact: Beverage Containers and Garbage Dumping

Beverage containers did not appear to occur at random within forests at a 24-km grain size (fig. 4a). In addition to the litter problem, if most beverage containers were from alcoholic beverages, then there were likely drinking problem areas as well. Forest land proximity to urban and built-up land explained much of the distribution of forests with beverage containers (fig. 4b). In urban land-use neighborhoods, impact varied with the municipality. Municipalities with widely recognized recycling initiatives, such as Chattanooga, TN, were more effective in


Land use
0.4 ha plots
black = forest
gray = nonforest
0 100 Kilometers
0 100 Miles
(a)
Forest probability (percent)
>=80
20 to <80
<20
No data
(b)

Plots (above) registered to 2.4 km grid cells. Then mean probability per cell calculated from 4.8 km radius (about 5 plots)

Figure 1.—*USDA Forest Service, Forest Inventory and Analysis (a) sample plots by land use, and (b) forest area probability (4.8-km radius), south central United States, 1988-1995.*

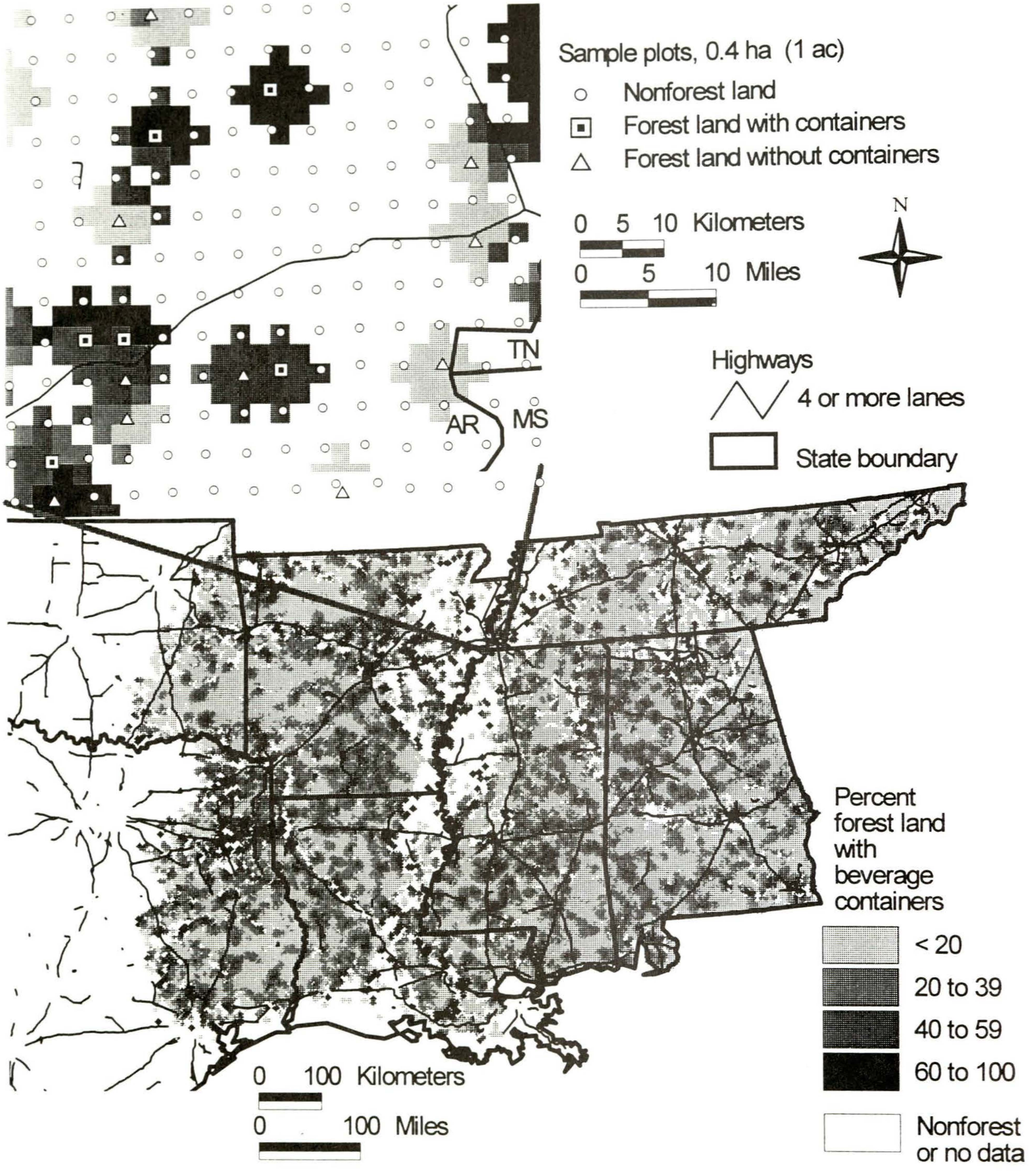

Sample plots, 0.4 ha (1 ac)
○ Nonforest land
▣ Forest land with containers
△ Forest land without containers
0 5 10 Kilometers
0 5 10 Miles
N
TN
AR
MS
Highways
4 or more lanes
State boundary
Percent forest land with beverage containers
< 20
20 to 39
40 to 59
60 to 100
Nonforest or no data
0 100 Kilometers
0 100 Miles

Figure 2.—*Beverage container probability in forests, south central United States, 1988-1995 and highways of four or more lanes (ESRI, Inc. 1996a). Inset: beverage container probability in forests near Memphis, TN. Probability estimates used a 4.8-km radius for forests and a 9.6-km radius for forest attributes. (For these and subsequent figures, nonforest land was defined as ≥80 percent probability of nonforest land use within a 4.8-km radius.)*

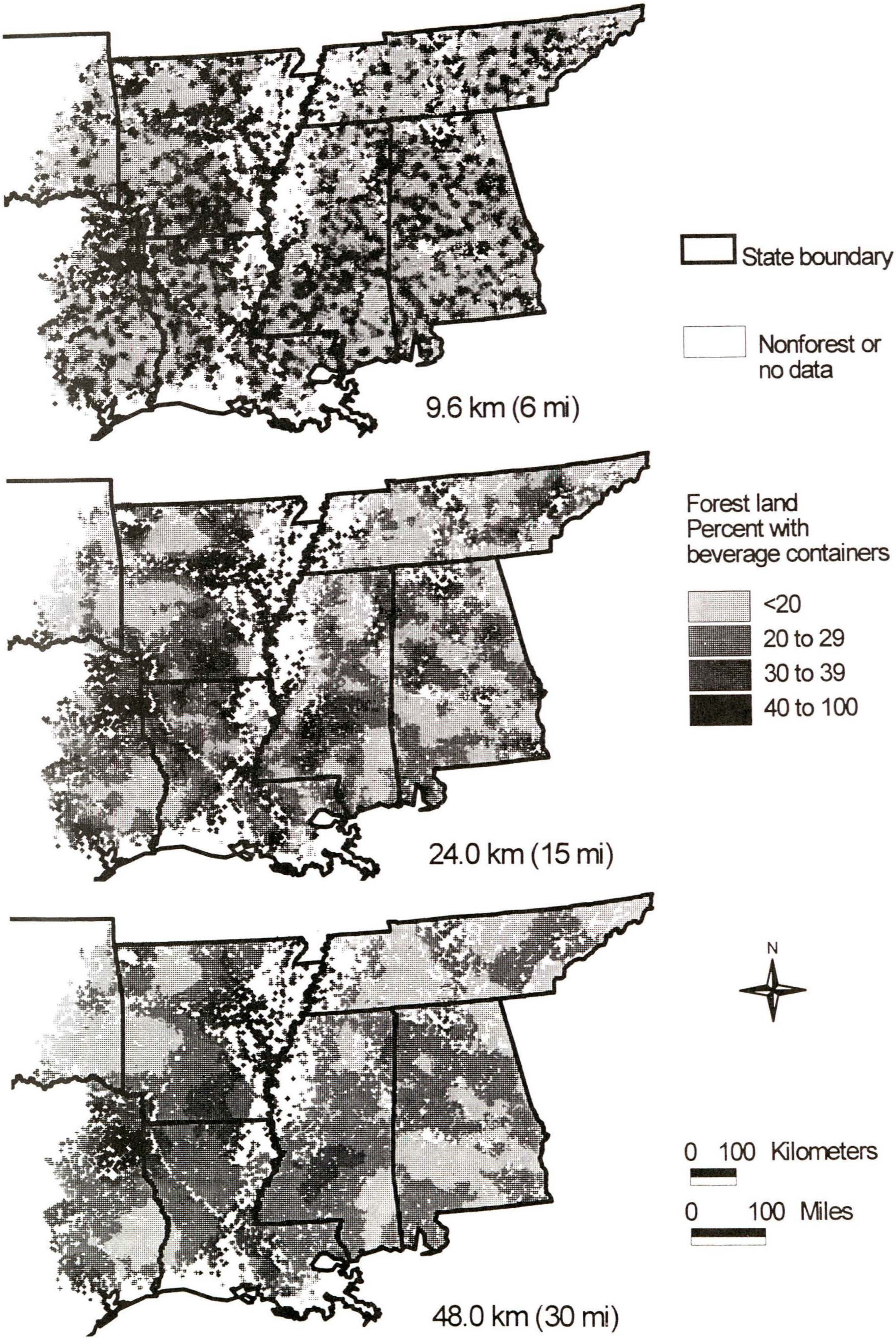

9.6 km (6 mi)
State boundary
Nonforest or no data
24.0 km (15 mi)
Forest land
Percent with
beverage containers
<20
20 to 29
30 to 39
40 to 100
N
48.0 km (30 mi)
0 100 Kilometers
0 100 Miles

Figure 3.—*Beverage container probability in forests at 9.6-, 24-, and 48-km radius grain sizes, south central United States forests, 1988-1995.*

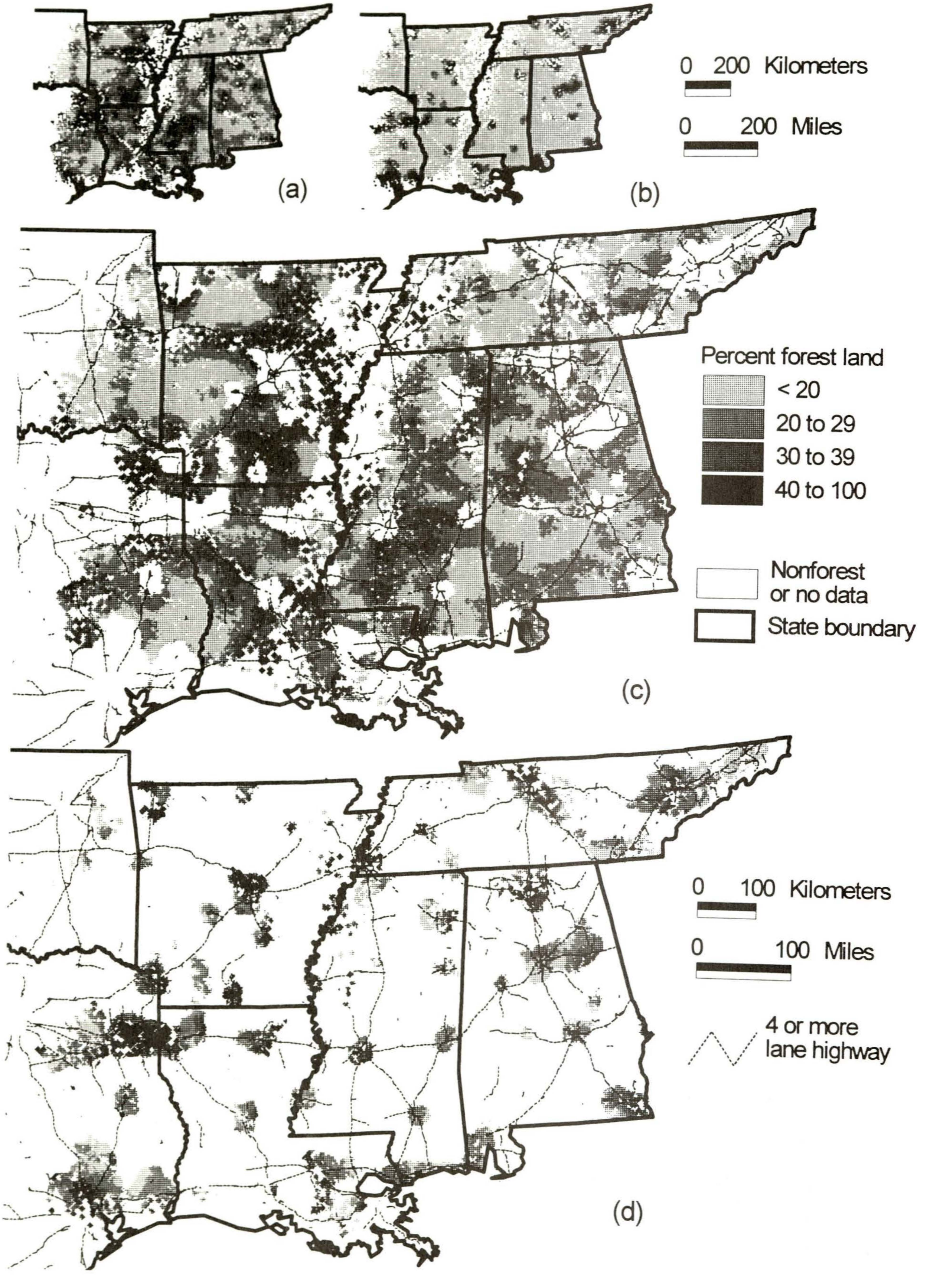

(a)
(b)
0 200 Kilometers
0 200 Miles
Percent forest land
< 20
20 to 29
30 to 39
40 to 100
Nonforest or no data
State boundary
(c)
0 100 Kilometers
0 100 Miles
4 or more lane highway
(d)

Figure 4.—(a) *Beverage container probability in forests; (b) forest land within 1.6 km of urban and built-up land $\geq$ 4 ha (10 ac); beverage container probability in forests (c) outside and (d) inside 1.6 km of urban and built-up land $\geq$ 4 ha (10 ac), 24-km radius grain size, south central United States, 1988-1995. Figures (c) and (d) include highways of four or more lanes.*

minimizing beverage containers than cities to the west (fig. 4c). In rural landscapes, forests with beverage containers were more commonly downstream of major water bodies, close to urban areas, and sparsely forested landscapes near areas of dense population. Potential problem locations in rural areas were near Hazen, AR; major roadways south of Jackson, MS; and Mt. Pleasant, TX (fig. 4d).

Garbage dumping in forested areas occurred more frequently near selected urban areas and major highways (fig. 5). Forests with garbage dumping were more prevalent downriver, downwind, and at lower topographic positions than those upriver, upwind, and at higher elevations. Most garbage dumping occurred near cities or along specific stretches of highways near populated areas. Other studies (Rudis 1995a, 1995b) found that older forest stands, smaller forest fragments, and those closest to roads were more likely to accumulate beverage containers and other litter.

Neighborhoods: Livestock Grazing in Forests

Livestock grazing in forests was not a random phenomenon. It occurred in selected areas more often than others (fig. 6a). Much was explained by the neighborhood, because most grazing in forests occurred in pasture-dominated landscapes (figs. 6b, 6c). Forests in these areas were vulnerable to periodic grazing, due to the proximity of the forests to livestock. Forests in nonpasture landscapes were less likely to be vulnerable. Some livestock grazing in forests occurred outside pasture-dominated landscapes (fig. 6d). Several of these locations may represent neighborhoods with active agroforestry operations, because they contained substantial forest industry land holdings or were pine plantations (and the western forest fringe of east Oklahoma and east Texas forest land). Further examination with more precise spatial estimates and correlates of browse potential, e.g., stand age and tree density class, may provide a more complete understanding of spatial relationships.

Interval Attribute: Fragmented Forests

I used forest fragment size class to illustrate one example of an interval attribute. Illustrated are mean fragment size using untransformed (fig. 7a) and logarithm transformed (fig. 7b) midpoint values. In this case, nonforest points did not contribute to the estimates. Comparisons with state maps showed that most of the large fragments were either in mountainous areas, such as the Boston Mountains of the Ozark National Forest, or in low-lying areas, such as the Atchafalaya Basin of Louisiana. The most fragmented forests were near major urban areas, the Mississippi Delta, and other cropland- or pasture-dominated land-use areas.

Co-occurring Distribution Patterns: Plantation, Industry, and Type

Perception of widespread occurrence of pine plantations periodically surfaces among those concerned with

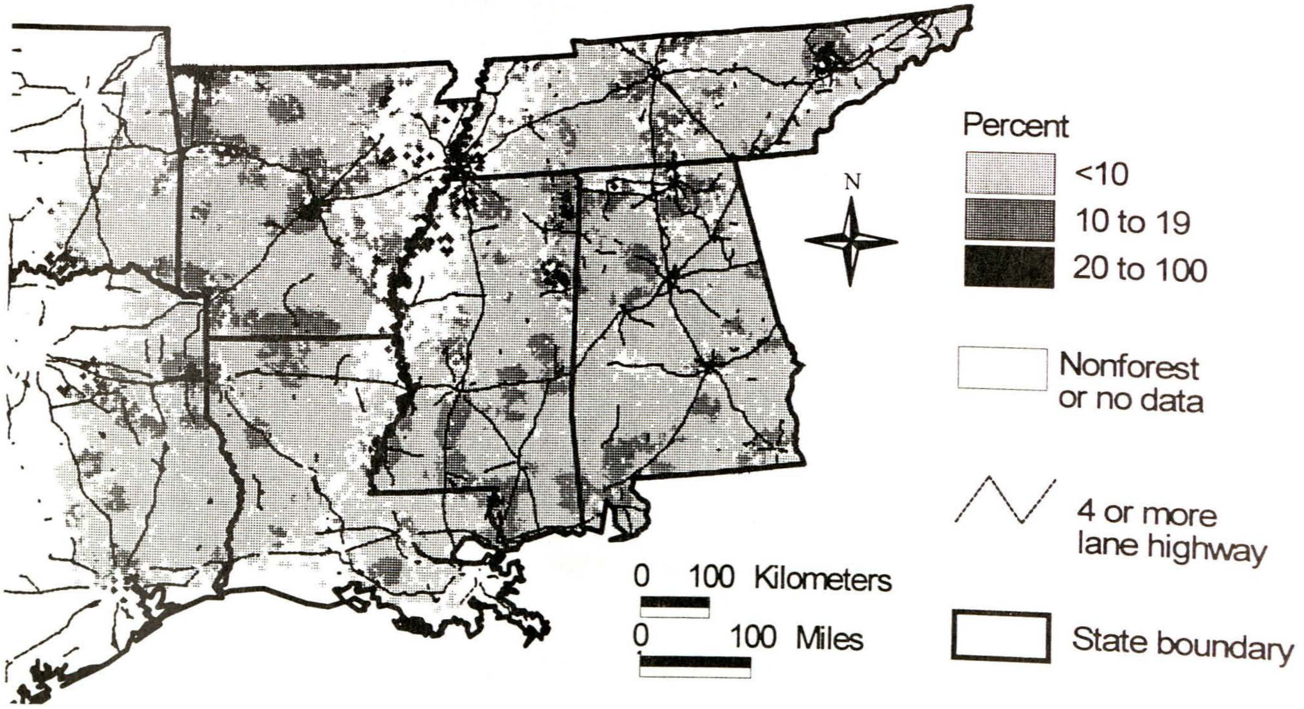


Figure 5.—*Garbage probability in forests, south central United States forests, 1988-1995, and highways of four or more lanes.*

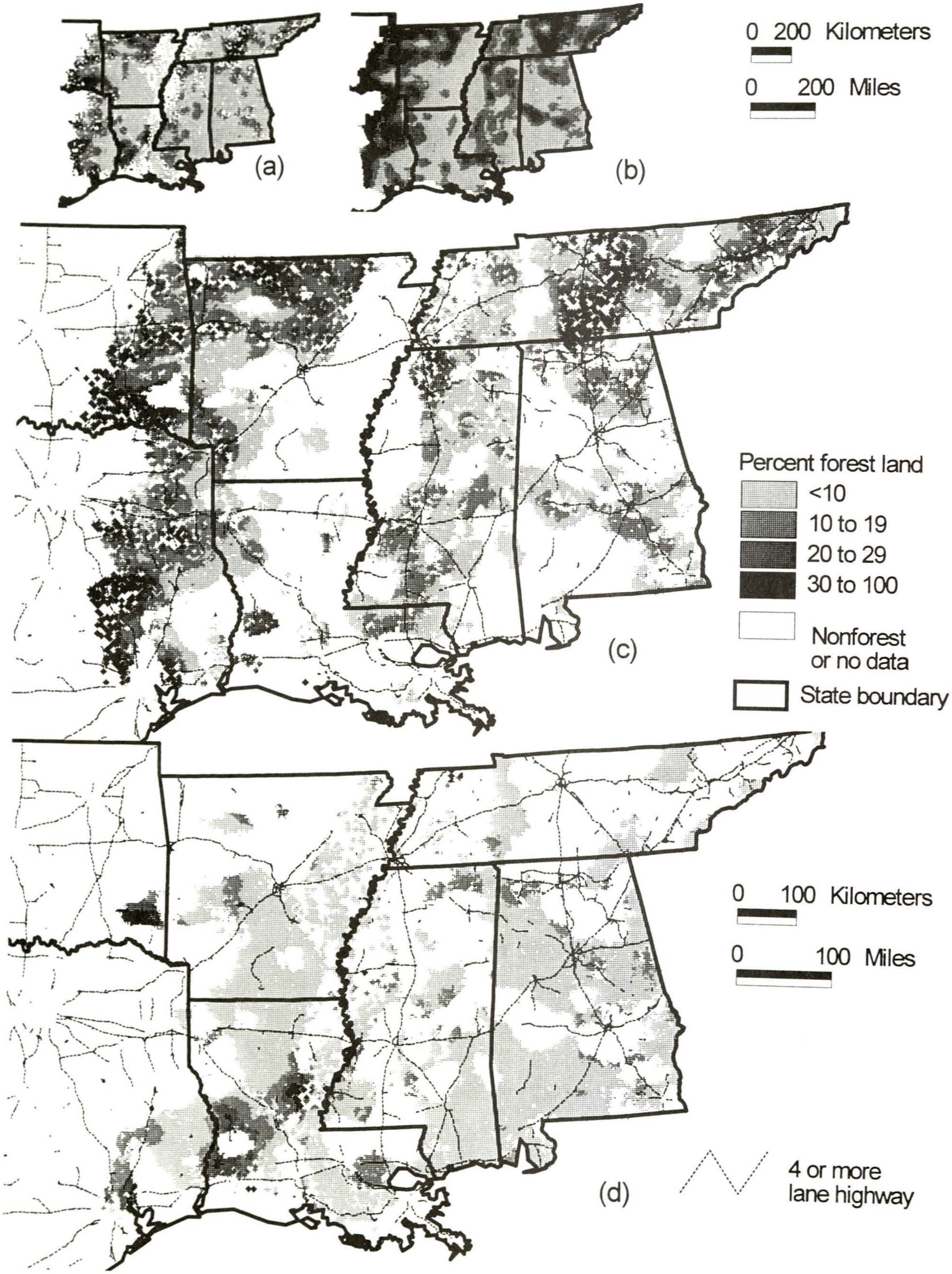

(a)
(b)
0 200 Kilometers
0 200 Miles
Percent forest land
<10
10 to 19
20 to 29
30 to 100
Nonforest or no data
State boundary
(c)
0 100 Kilometers
0 100 Miles
4 or more lane highway
(d)

Figure 6.—*Probability of (a) livestock grazing in forests (c) within and (d) outside pasture neighborhoods, and (b) pasture land probability, south central United States forests, 1988-1995. Figures (c) and (d) include highways of four or more lanes.*

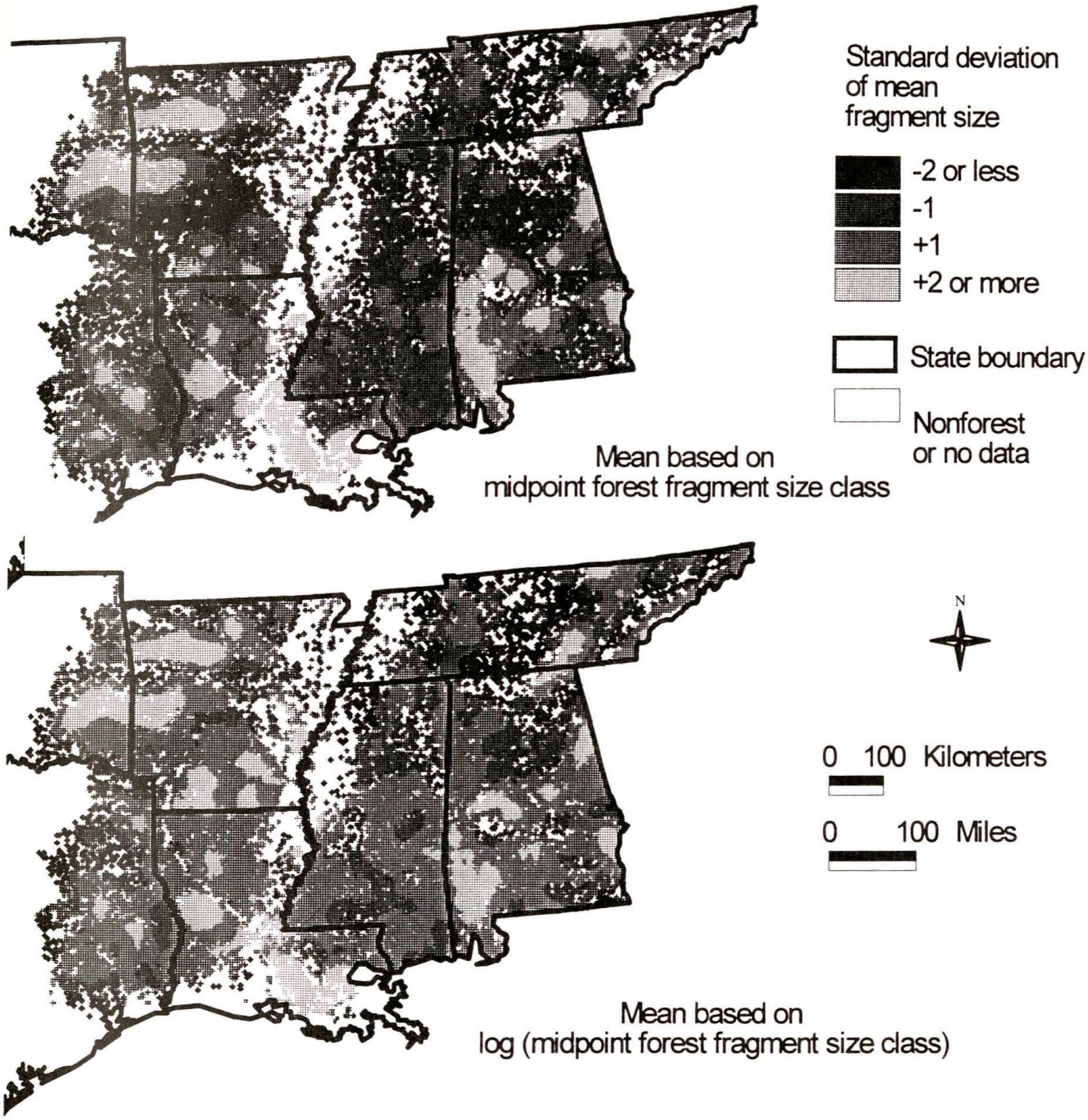

Standard deviation of mean fragment size
-2 or less
-1
+1
+2 or more
State boundary
Nonforest or no data
Mean based on midpoint forest fragment size class
N
0 100 Kilometers
0 100 Miles
Mean based on log (midpoint forest fragment size class)

Figure 7.—*Fragmented forest land probability, using (a) untransformed midpoint values (b) logarithm transformed midpoint values, south central United States forests, 1988-1995.*

biological diversity. Other tabular or county-scale information noted that they were widespread, concentrated in selected regions (Boyce and Martin 1993, Rudis 1998), and on the increase (Birdsey and McWilliams 1986, Rudis 1991). At a grain size of 24-km radius, forest plantation distributions were widespread, with very few areas containing plantation probability greater than 40 percent (fig. 8a). While most plantations were of loblolly pine, and many plantations were owned by forest industry, there was not a one-to-one correspondence with forest plantations and forest industry land (fig. 8b), or with the distribution of loblolly pine forest type (fig. 8c). Although not examined here, plantation distribution patterns may be more closely correlated with pulp mill proximity or regionally successful forestry incentive programs.

ACKNOWLEDGMENTS

Thanks to Debbie Beardsley, Pacific Northwest Research Station, Portland, OR, USA; Dennis Jacobs, Southern Research Station, Starkville, MS, USA; and Bernie Parresol and Greg Reams, Southern Research Station, Asheville, NC, USA, for their constructive remarks on an earlier presentation of the manuscript.

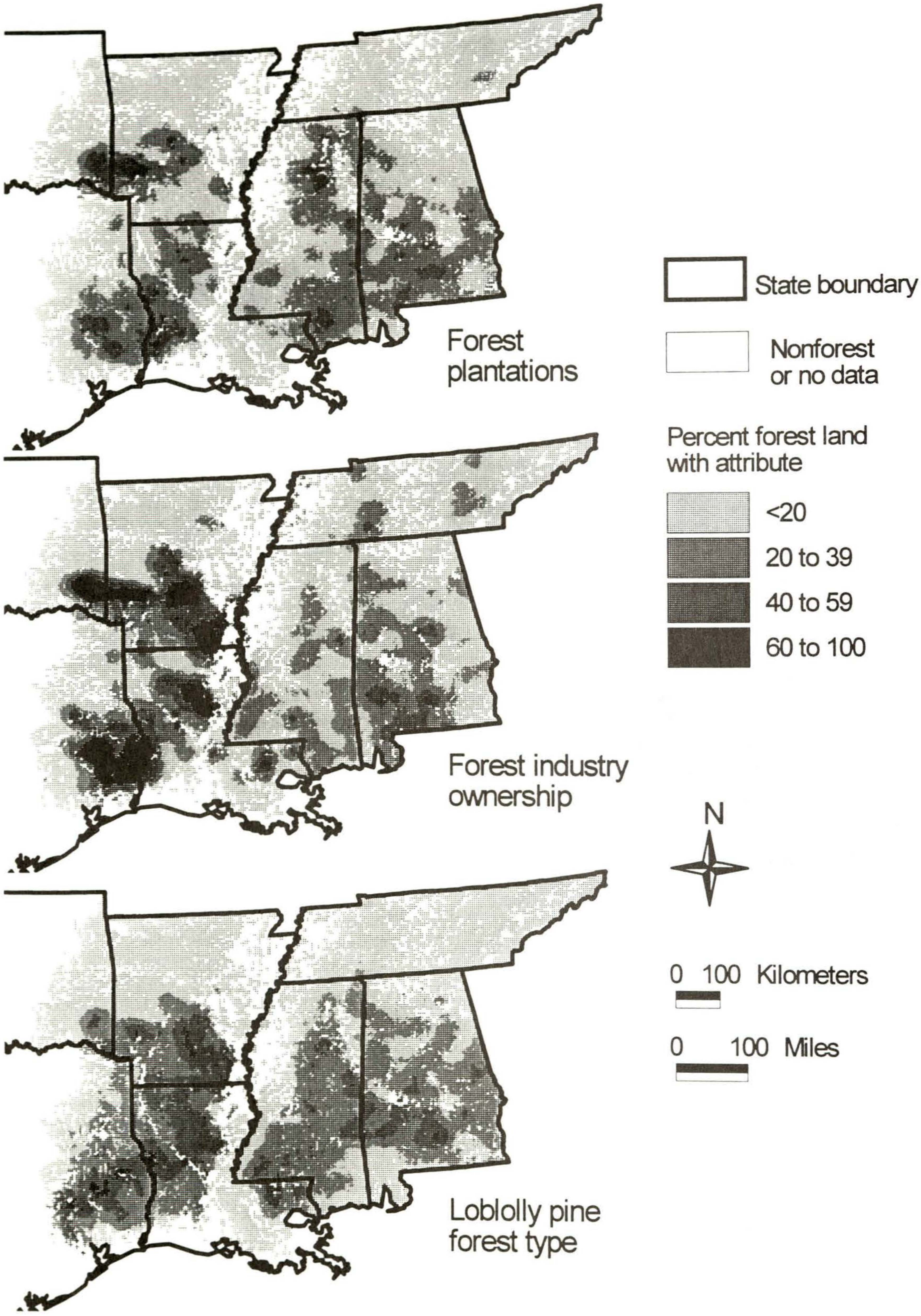

Forest plantations
Forest industry ownership
Loblolly pine forest type
State boundary
Nonforest or no data
Percent forest land with attribute
<20
20 to 39
40 to 59
60 to 100
N
0 100 Kilometers
0 100 Miles

Figure 8.—*Probability of (a) forest plantations, (b) forest industry ownership, and (c) loblolly pine forest type, in south central United States forests, 1988-1995.*

LITERATURE CITED

Barlow, S.A.; Munn, I.A.; Cleaves, D.A.; Evans, D.L. 1998. The effect of urban sprawl on timber harvesting: a look at two southern States. Journal of Forestry. (9): 96.

Befort, W.A.; Luloff, A.E.; Morrone, M. 1988. Rural land use and demographic change in a rapidly urbanizing environment. Landscape and Urban Planning. 16: 345-356.

Birdsey, Richard A.; McWilliams, William H. 1986. Midsouth forest area trends. Resour. Bull. SO-107. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 17 p.

Boyce, Stephen G.; Martin, William H. 1993. The future of the terrestrial communities of the southeastern United States. In: Martin, W.H.; Boyce, S.G.; Echternacht, A.C., eds. Biodiversity of the southeastern United States: upland terrestrial communities. New York: John Wiley and Sons: 339-366.

Deutsch, Clayton V.; Journel, Andre G. 1998. GSLIB: Geostatistical software library and user's guide, 2d ed. New York: Oxford University Press. 369 p.

ESRI, Inc. 1996a. ESRI data and maps. Volume 1. Redlands, CA: Environmental Systems Research Institute, Inc. Compact Disc.

ESRI, Inc. 1996b. Working with the ArcView Spatial Analyst. Redlands, CA: Environmental Systems Research Institute, Inc.: 2-11.

FIA Staff. 1994. Forest survey inventory work plan: Arkansas 1994-1995. Starkville, MS: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, Forest Inventory and Analysis Unit. 61 p. Appendix A. 50 p.; Appendix B: Other forest resources. 19 p.

Hershey, Rachel Riemann. 1996. Understanding the spatial distribution of tree species in Pennsylvania. In: Mowrer, H.Todd; Czaplewski, Raymond L.; Hamre, R.H., tech. coords. Spatial accuracy assessment in natural resources and environmental sciences: 2d International Symposium. Gen. Tech. Rep. RM-277. Ft. Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 73-82.

Isaaks, Edward H.; Srivastava, R. Mohan. 1989. An introduction to applied geostatistics. New York: Oxford University Press. 561 p.

Rudis, Victor A. 1987. Recreational use of forested areas by Alabama residents. Res. Pap. SO-237. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 37 p.

Rudis, Victor A. 1991. A recreation and landscape perspective of Alabama's changing forest environment: the human character of forests. In: Jones, R.H., ed. Proc. Alabama's forest resources: past, present and future; 1991 May 29-30; Auburn University, AL. Auburn University, AL: Auburn University School of Forestry; Alabama Cooperative Extension Service: 93-114.

Rudis, Victor A. 1995a. Human intrusions in forested areas: southern United States examples. In: Working in a world dominated by humans: theory and practice of landscape ecology. Program abstracts of the 10th annual U.S. landscape ecology symposium; 1995 April 22-26; Minneapolis, MN. Minneapolis, MN: International Association of Landscape Ecology and University of Minnesota: 161.

Rudis, Victor A. 1995b. Regional forest fragmentation effects on bottomland hardwood community types and resource values. Landscape Ecology. 10(5): 291-307.

Rudis, Victor A. 1998. Regional forest resource assessment in an ecological framework: the southern United States. Natural Areas Journal. 18(4): 321-334.

Rudis, Victor A. (In press.) Landscape and regional patterns in Arkansas' forest ecosystems. (preprint draft 44 p.) In: Guldin, James M., comp. Symposium on Arkansas forests; 1997 May 30-31; Little Rock, AR. Gen. Tech. Rep. SRS-. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southern Research Station.

Rudis, Victor A.; Tansey, John B. 1995. Regional assessment of remote forests and black bear habitat from forest resource surveys. Journal of Wildlife Management. 59(1): 170-180.

Adequacy of Different Experimental Designs for Eucalyptus Spacing Trials in Portuguese Environmental Conditions

Paula Soares and Margarida Tomé

Abstract.—In Portugal, several eucalyptus spacing trials cover a relatively broad range of experimental designs: trials with a non-randomized block design with plots of different size and number of trees per plot; trials based on a non-systematic design in which spacings were randomized resulting in a factorial arrangement with plots of different size and shape and equal number of trees per plot; trials based on a completely randomized block design with different plot sizes and different numbers of trees per plot. Limitations and advantages of these experimental designs, when applied to Portuguese climatic and edaphic conditions, are discussed based on theoretical principles and empirical observations. This analysis suggests that, when the main objectives are to improve databases and to sample extremes of stand conditions for modeling purposes, more importance should be placed on the practical consequences in the prediction of stand characteristics than on the theoretical aspects.

Portugal, located between the parallels 42º and 37º north and the meridians 9º and 6º west of Greenwich, is the most occidental country of the European Continent. Continental Portugal has an area of 8.900×103 ha. The Atlantic Ocean limits Portugal along the west coast at an extent of 848 km, while the terrestrial frontier with Spain is 1,232 km long. The Portuguese climate can be considered Mediterranean tempered by oceanic influence, with long hot and dry summers; the Mediterranean influence is particularly dominant in the southern half of the country. Portugal presents an evident contrast between the north and the south of the Tagus River (Alves *et al.* 1990): to the north, the average altitude is 421 m and increases to more than 400 m in 47.6 percent of the area; to the south, the average altitude is only 169 m and it is lower than 400 m in 97 percent of the area. Portugal also spans a great diversity of geological formations. The half-arid and dry sub-humid areas present, in general, soils with medium to strong slopes that are poor in organic matter and have a low capacity to retain and to store water. Low to medium fertility and a high probability of erosion normally characterize these Leptosols, Cambiosols, and Luvisols. Soils with high potential production and great resistance (Fluvisols, Vertisols, Calcisols, and Podzols) occur only to a small extent in Portugal (DGF 1998).

Eucalyptus globulus, a fast-growing tree species with free growth without pre-formed overwintering buds, was introduced in Portugal 150 years ago. At present, it is the third most represented forest species in Portugal, covering 20.7 percent of the total forestland and occupying an area of 3,358.8×103 ha (DGF 1998). The success of eucalyptus was a consequence, in part, of the adequacy of good environmental conditions in a substantial part of the country for eucalyptus growth. In fact, eucalyptus species are highly productive even in areas where drought and nutrient stress occur, in spite of the fact that their productivity is strongly dependent on soil water and nutrient availability (Florence 1996, Pereira 1989). In Portugal, eucalyptus plantations are mainly used by the pulp industry and are intensively managed as a short-rotation coppice system, in which the first cycle of planted seedlings (single stem) is followed by two or three coppiced stands, with an average cutting cycle of 10 years. To be able to make accurate growth predictions, data from permanent plots and experimental trials (where there is some control of the factors influencing tree growth) are needed. The spacing trials allow for the study of the relation between stand development and stand density. This knowledge is crucial for the silviculture of short-rotation crops, in which the main purpose is the quick occupation of the site and exploitation of its available resources to maximize production, within the limits of sustainable forest management. The Stora Celbi Company established the first spacing trial in 1975 at the Furadouro site (center of Portugal and close to the sea). In 1993, the Department of Forestry initiated a research project mainly to study the influence of spacing on the growth and productivity of eucalyptus stands on different sites. Seven spacing trials were installed in different

---

Researcher and Associate Professor of Forestry, respectively, Department of Forestry, Instituto Superior Agronomia, Tapada Ajuda, 1399 Lisboa Codex, Portugal.

regions and over different time periods (only four survived!). Problems finding an adequate experimental design began. Different experimental designs were tried. In the following paragraphs, we present some of the problems and/or benefits that were found in relation to each one of the experimental designs that were tried.

REFLECTIONS

What is Desirable in a Spacing Trial?

To be able to estimate the behavior and the production of future stands, it is necessary to have both stand simulators and silviculture experiments that will allow for the definition of the relationships between growth, stand conditions, and stand treatments. These experiments help to improve databases and to sample extremes of stand conditions that are essential even if they will never be applied; they are fundamental to properly define the response surface for growth models (Vanclay 1994). The analysis of tree growth response to stand density level implies, compulsorily, the installation of spacing trials and therefore the selection of an experimental design. Questions arise that are related not only to the experimental design but also to the number of trees per plot and the plot size: (1) different number of plants per plot in plots with the same size; (2) equal number of measured plants per plot in plots with the same size; (3) equal number of plants in plots with different sizes. Lin and Morse (1975) stated that, from the statistical point of view, a choice must be made between (1) and (2), but from the economic point of view, option (3) is much more attractive. If the main objective is to analyze the influence of spacing in stand yield, the quality of the yield estimation per hectare will be better when based on plots of the same size. When plots of different sizes are selected, the statistical analysis can become complex if the variance components cannot be assumed to be homogeneous.

The definition of the plot size is an ambiguous point: plots cannot be excessively small, because that results in biased estimates of the stand parameters, but they must be sufficiently small to guarantee homogeneity within the block. Very small plot sizes are undesirable and sometimes unusable as a basis for growth models and for estimations of mortality and diameter distributions (Curtis 1983). Small plots can also result in biased site index estimates, especially when the dominant height is based on a number of the largest dbh trees per unit area. Curtis (1983) recommended that a site index estimate should not be based on fewer than four trees per plot. However, to minimize the experimental error, homogeneous plots are required and that means minimizing within-plot variance (Vanclay 1994). This homogeneity is related not only to the natural site conditions but also to the site preparation methods. Site preparation machines can restrict the distances between rows especially if deep mobilizations or subsoil plowing are the options; the minimum distance in which they normally can operate is 3 m between rows. Experimental designs that require a large number of plots within homogeneous stand conditions must be avoided because that forces the use of small plots. The plots must be subjectively located with subsequent random assignment of treatments and must be installed with buffer strips between adjacent treatments.

The experimental designs normally used in spacing trials can be systematic (e.g., Nelder 1963), non-systematic with a factorial base (Lin and Morse 1975), or non-systematic with randomized blocks (e.g., Montgomery 1991). However, the validity of a certain experimental design can only be assessed in relation to the uses to which it is put (Mead 1979, Cousens 1996). Systematic designs allow the use of a wide range of spacings in a single experimental trial, which is most adequate if the space and the plant material are limited. They can be used to define the optimal spacing or the effect of rectangularity, but presumably they are not the most adequate because of the asymmetric density around each tree (Amateis *et al.* 1988). The area per plant and/or the rectangularity of the space available to a plant changes in some consistent fashion over the different parts of the grid of plants (Nelder 1962). Systematic designs are efficient when the explanation of the relationships is of primary importance using regression techniques (Amateis *et al.* 1988). One advantage of the randomized block design is that randomized designs provide, when the plot-treatment condition holds, an unbiased estimate of the variance of treatments effects, also giving unbiased estimates of the mean (Nelder 1962). The randomization allows for the use of analysis of variance techniques as well as the fitting of response surfaces with regression methods (Amateis *et al.* 1988). Nelder (1962) referred to some disadvantages of randomization when applied to spacing trials: the difficulty to put together all the plots if a square plot pattern and an equal number of trees per plot were selected; the large number of trees associated with the close spacings when plots of the same size were selected. He also noted the difficulty of maintaining small blocks when using buffer trees between treatments.

The Spacing Trials in Portugal

Several eucalyptus spacing trials in Portugal were installed by pulp companies or by the Department of Forestry in collaboration with these companies (table 1). Except for the Alto do Vilão trial, an equal number of trees per plot was used within a trial; the number of measured trees per plot ranged from 16 to 360. This work focuses on some of the spacing trials installed by the Department of Forestry and by the Stora Celbi Company.

Table 1.—*Principal characteristics of the eucalyptus spacing trials in Portugal*

Designation	Responsible	Year of plantation	Number blocks	Number plots/block	Nº of measured trees/plot	Spacings (m×m)
Alto Vilão	Stora Celbi	1975	2	5	80-360	3×2 3×3 4×3 4×4 4×5
Qta Paço	Stora Celbi	1990	2	5	196	2×1 3×1 2×2 3×2 3×3
Cabroeira	Silvicaima	1990	2	5	16	3×1.5 3×2 3×2.5 3×3 3×3.5
Oliveirinha	Silvicaima	1990	4	6	25	3×1.5 3×2 3×2.5 3×3 3×3.5 3×4
P. Cavaleira	Silvicaima	1990	4	5	16	3×1.5 3×2 3×2.5 3×3 3×3.5
Q^{ta}Laurentim	Silvicaima	1992	4	6	25	3×1.5 3×2 3×2.5 3×3 3×3.5 3×4
Vilar Luz	DEF[1]	1993	3	12	64	2×1 2×2 2×3 2×4 3×1 3×2 3×3 3×4 4×1 4×2 4×3 4×4
Ribeiro Seixo	DEF[1]	1994	2	12	64	2×1 2×2 2×3 2×4 3×1 3×2 3×3 3×4 4×1 4×2 4×3 4×4
Vale Bezerra	DEF[1]	1994	2	8	64	3.5×1 3.5×2 3.5×3 3.5×4 4×1 4×2 4×3 4×4
Agolada	DEF[1]	1994	2	7	3×15[2]	1×1 2×1 2×2 3×3 4×1.5 4×2 4×4
Nicolaus	DEF[1]	1996	3	5	4×15[2]	3×0.5 3×1 3×2 3×3 3×4

[1] DEF, Department of Forestry; 2 were established with clonal material, with the clone as a split inside each plot (3 and 4 clones, respectively, in Agolada and Nicolaus).

The experimental designs of the spacing trials listed in table 1 differ (fig. 1):

a) Alto do Vilão: each block is a combination of five plots with different sizes and shapes that were distributed without previous randomization; the blocks are located side by side and the spacings were distributed according to decreasing density in one of the blocks and increasing density in the other block.

b) Quinta do Paço: each block is a combination of five plots with different sizes and shapes that were randomly distributed but restricted by the position of the 2×2 and 2×1 spacings that were placed side by side.

c) Ribeiro do Seixo, Vale da Bezerra, and Vilar de Luz: randomized block design, with three spacing factors between rows and four spacing factors within rows, resulting in factorial combinations of spacings occupying plots of unequal size with the same number of trees.

d) Agolada: randomized block design with plots of unequal size with the same number of trees.

e) Nicolaus: randomized block design with plots of unequal size with the same number of treesÑthe distance between rows is constant.

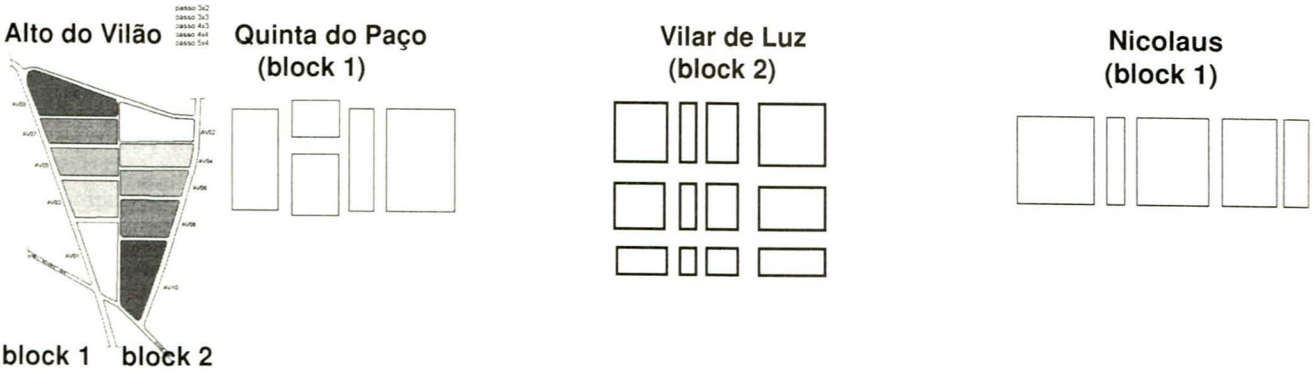


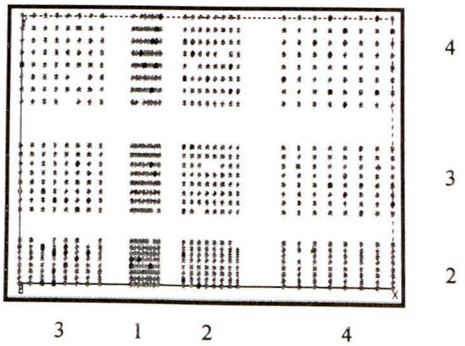
Figure 1.—*Some of the spacing trials in Portugal (all the plots are surrounded by at least two buffer rows).*

The experimental design used in Ribeiro do Seixo, Vale da Bezerra, and Vilar de Luz (randomized block design with factorial combination of row and between-row spacings resulting in plots of unequal size with the same number of trees) was not the most adequate for Portuguese environmental conditions. In fact, the advantages of this design (e.g., the high number of initial densities tested and the opportunity to test the rectangularity effects) are offset by the difficulty of finding a homogeneous block of such dimensions (approximately 1.2 ha). The Vilar de Luz spacing trial is a good example (table 2). It is located on the north coast of Portugal in a region where the water is not a serious restriction during the summer and where the soil presents good conditions for forest growth. When the total block is considered, the dominant trees, defined as the 100 largest trees in dbh per hectare, are located mainly in the plots corresponding to spacings 4×4 and 3×2; some plots have a no or only a small number of dominant trees (4×2 and 3×4). Note that this analysis is based on measurements at a very young age (21 months), before competition is evident. The difficulty of finding homogeneous areas restricts the number of measured trees in each plot. In the closest spacings of these trials, site index estimates are based on only one dominant tree, making it difficult to study the effect of spacing on dominant height, one of the main questions in relation to the effect of spacing on stand parameters.

The problem of soil heterogeneity is also evident in the Quinta do Paço trial at a very young age (31 months). When the total area of the plot is considered, in the widest spacing, three of the four dominant trees are located in the same quarter of the plot (table 3). In this trial the influence of the lack of homogeneity is also evident in the mortality. Westoby (1984) noted that a stand with a natural mortality greater than 20 percent can be considered self-thinning. If only a quarter of the plot (III), corresponding to the 2x1 spacing of the Quinta do Paço trial, was considered, it could be concluded that the stand was self-thinning. However, only at 67 months, natural mortality greater than 20 percent was detected for the first time in the whole plot. The influence of soil heterogeneity is also evident in basal area, although less so. In fact, the fewer number of living trees per hectare associated with subplot III was offset by a slight increase in the quadratic mean diameter resulting from the lower intraspecific competition intensity or from the higher site productivity (or a mix of both) (table 3). However, at that age, the effects of the intraspecific competition were not yet evident in the plot.

The soil heterogeneity at a small scale is also evident in the Agolada spacing trial located in the center-south of Portugal. The soils are Luvic Arenosols with several layers of sandy texture intermixed with layers that have a higher content of lime and clay with a high proportion of coarse material of natural quartz (Pacheco et al. 1997), a common soil type in Portugal. This trial has been the object of intensive monitoring, including not only biometric measurements, but also measurement of physiological parameters and soil water. Each block has

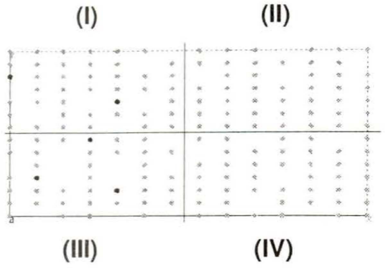
Table 2.—*Values of dominant height when the total block and each plot are considered (dominant trees are the 100 largest trees in dbh per hectare)–Vilar de Luz spacing trial at 21 months*

Spacing (m×m)	**h_{dom} (m)**	**$S_{h,t}$ [1]**	**Number of dominant trees**	**Position of the dominant trees when the total block is considered**
1x2	6.8	*20.0*	1	
1x3	6.3	19.2	2	
1x4	5.9	18.4	3	
2x2	6.0	18.6	3	
2x3	4.6	15.7	4	
3x2	5.6	17.8	4	
4x2	5.3	17.1	5	
2x4	5.5	17.6	5	
3x3	4.8	16.1	6	
4x3	5.3	17.1	8	
3x4	5.9	18.4	8	
4x4	5.6	17.8	10	
all block	6.6	19.7	58	

---

[1] Site index defined as the mean height of the dominant trees, 100 largest trees in dbh per hectare, at 10 years - estimated according to Tomé (1990) and based on the measurement of July 1995 (21 months).

Table 3.—*Values of dominant height when all the plot and fractions of the plot are considered (dominant trees are the 100 largest trees in dbh per hectare)–spacing 2x1 of the Quinta do Paço spacing trial at 31 months*

Spacing 2×1	h_{dom} (m)	$S_{h,t}$[1]	Number of dominant trees	Mortality (%)	BA[2] (m^2ha^{-1})	Position of the dominant trees in a plot of 392 m^2
I	12.0	24.6	1	14.3	1.91	
II	11.0	23.1	1	8.2	1.79	
III	13.3	26.4	1	322.4	1.87	
IV	11.1	23.3	1	12.2	1.77	
all plot	12.3	25.0	4	9.7	1.83	

[1] Site index defined as the mean height of the dominant trees, 100 largest trees in dbh per hectare, at 10 years - estimated according to Tomé (1990) and based on the measurement of November 1992 (31 months); 2 basal area; five trees were marked because the fourth and fifth largest trees presented the same dbh.

an area of 0.5 ha and, in spite of the fact that the blocks were established along the contour lines to minimize the heterogeneity inside the blocks, much variability was still found inside each block. Soil heterogeneity effects were particularly evident in block 2 during May and October 1996. In this block, dbh and height growth were higher in the 3×3 spacing than in the 4×4 spacing. In fact, the dbh increment was approximately 8 mm for the 4×4 spacing and 11.5 mm for the 3×3 spacing; the height increment was approximately 20 cm for the 4×4 spacing and 150 cm for the 3×3 spacing. Different soil water profiles and different soil water extraction patterns were the main cause for this unexpected behavior. Figure 2 represents the evolution of the soil water extraction patterns by spacing during the growing season (May until October) up to 2.6 m deep. The pattern associated with the first measurement corresponds to the soil water profile. It was observed that, at 16 months, the volumetric water content along the total profile was different for both spacings, reflecting different growth conditions. An accurate observation showed that plot 3×3 is located above a sandstone layer with very low permeability, maybe with a physical obstacle hindering the lateral movement of water originating from a zone of water accumulation highly favorable to plant growth (Pacheco *et al.* 1997).

The Alto do Vilão trial, established with a non-randomized design, resulted in a good tool to use in analyzing the effect of spacing on dominant height growth. It was decided to install a spacing trial with two blocks located side by side where the spacings were distributed according to decreasing density in one of the blocks and increasing density in the other block (fig. 1). A different relationship between dominant height and spacing was observed in both blocks (fig. 3). In fact, a north/south productivity gradient was detected. When the dominant

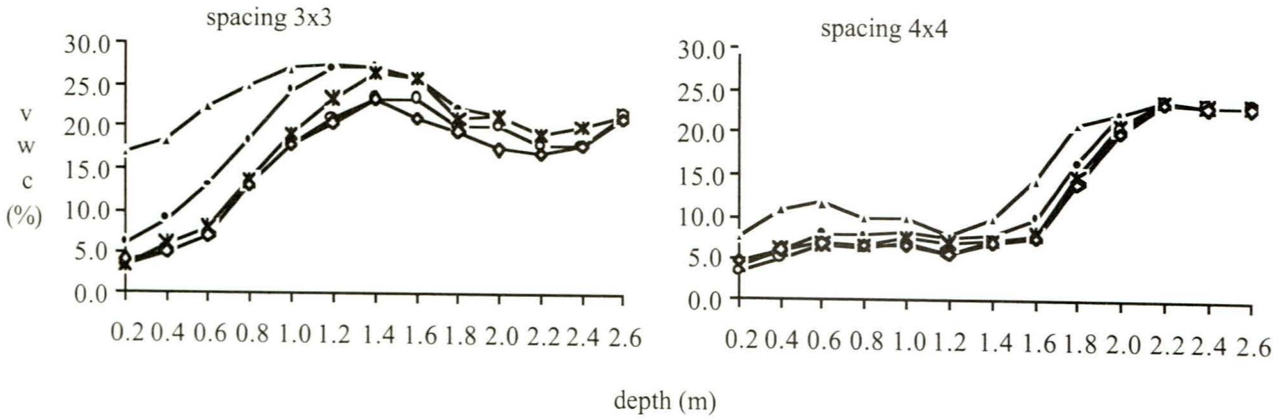


Figure 2.—*Evolution of the pattern of water extraction by spacing during the growing season (May Å until October Ø) up to 2.6 m deep; vwc, volumetric water content (in: Pacheco* et al. *1997).*

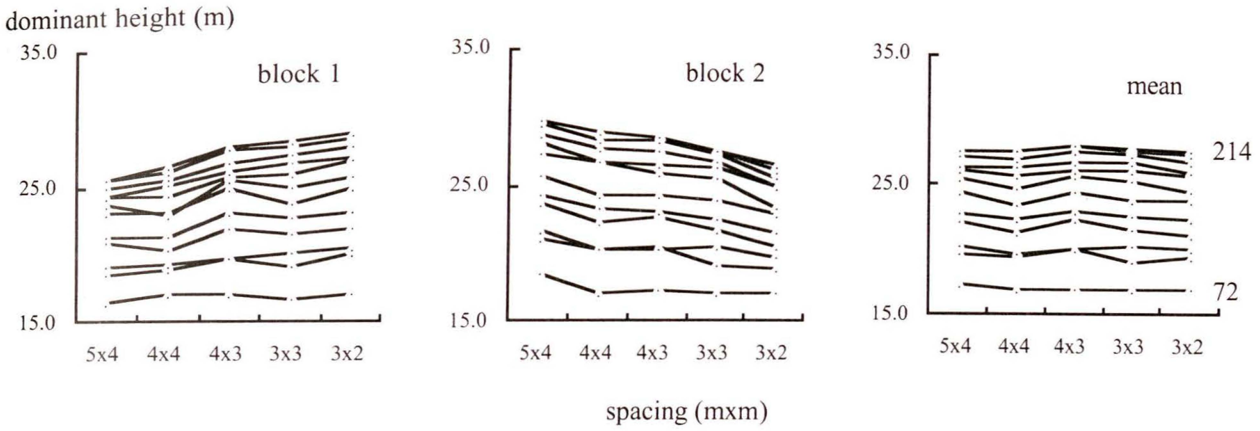


Figure 3.—*Relation between dominant height and spacing at the Alto do Vilão trial (72-214 months).*

height associated with the spacing is estimated by the mean of both blocks, the effect of the productivity gradient is eliminated. The third graph in figure 3 suggests that dominant height is independent of the planting density.

FINAL CONSIDERATIONS

In Portugal, the edaphic and the climatic conditions limit the dimension of the blocks, mainly when the homogeneity within the plots and blocks needs to be guaranteed. This need of homogeneity is particularly important for eucalyptus because it is very sensitive to soil water content. The non-systematic design with a factorial base proposed by Lin and Morse (1975) was the first design selected by the team from the Department of Forestry responsible for the installation of some of the spacing trials. The selection was based on the opportunity to test, in the same trial, a great number of spacings. Four spacing trials were installed, but this design was abandoned after the first measurements. The team found it impossible to guarantee homogeneity in 1.2-ha blocks. Also during this period, strong night-frosts affected the initial development of these trials, and the mortality, although not related to spacing, was not constant within the blocks.

After trying other experimental designs, it was found that a good alternative could be an experimental design based on plots of unequal size but with the same number of measured trees. However, in the closest spacing, more plants should be planted to provide an opportunity to measure at least four dominant trees. Twelve spacing designs should be rejected and instead only five spacings considered. The distance between rows should be fixed within the trial and defined considering the fact that the pulp companies normally weed the stands with mechanical equipment to control weed competition and to prevent forest fires. Three meters between rows is the suggested minimum distance to test. At least two guard rows must buffer each plot.

The choice of the experimental design most adequate to Portuguese conditions cannot be unique. However, when the main objectives are to improve databases and to sample extremes of stand conditions for modeling purposes, more importance should be placed on the practical consequences of predicting stand characteristics than on the theoretical aspects.

ACKNOWLEDGMENTS

The following people reviewed this manuscript: José Tomé, Teaching Assistant in the Department of Forestry, Instituto Superior de Agronomia, Lisboa. Portugal, and Ralph Amateis, Research Associate, Department of Forestry, Virginia Tech, Blacksburg, VA, USA.

Financial support for this project was provided by the projects JNICT PBIC/1482/AGR/92 "Competição em povoamentos florestais sob diferentes situações de *stress* ambiental," CE AIR 92.1678 "Improvement of eucalypt management. An integrated approach: breeding, silviculture and economics," PAMAF 4025 "Influência do compasso no crescimento e produção de plantações de *Eucalyptus globulus* Labill. e *Pinus pinaster* Ait. em diferentes ambientes ecol—gicos."

We acknowledge unpublished data provided by the pulp company Stora Celbi and information about the spacing trials provided by the pulp company Silvicaima.

LITERATURE CITED

Alves, A.M.; Pereira, J.S.; Borges, J.G.C.; Borges, G.C.; Carvalho, P.O.; David, J.S.; Gonçalves, J.; Madeira, M.; Onofre, N.; Valente, F. 1990. Impactes ambientais e sócio-económicos do eucaliptal em Portugal. Departamento de Engenharia Florestal, Instituto Superior de Agronomia, Lisboa, 105 p.

Amateis, R.; Burkhart, H.; Zedaker, S. 1988. Experimental design and early analyses for a set of loblolly pine spacing trials. In: Ek, A.R.,; Shifley, S.R.; Burk, T.E., eds. Proceedings of the IUFRO forest growth modelling and prediction conference; 1987 August 23-27; Minneapolis, MN. Gen. Tech. Rep. NC-120, vol. 2. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station: 1058-1065.

Cousens, R. 1996. Design and interpretation of interference studies: are some methods totally unacceptable? New Zealand Journal of Forestry Science. 26: 5-18.

Curtis, R.O. 1983. Procedures for establishing and maintaining permanent plots for silvicultural and yield research. Gen. Tech. Rep. PNW-155. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 56 p.

DGF. 1998. Resultados preliminares da 2ª fase da 3ª Revisão do Inventário Florestal Nacional. Site Web da DGF: http://www.dg-florestas.pt

DGF. 1998. Grupo de Coordenação Interna do Programa de Acção Nacional de Combate à Desertificação.

Florence, R.G. 1996. Ecology and silviculture of Eucalypt forests. CSIRO, Austrália. 413 p.

Lin, C.S.; Morse, P.M. 1975. A compact design for spacing experiments. Biometrics. 31: 661-671.

Mead, R. 1979. Competition experiments. Biometrics. 35: 41-54.

Montgomery, D. 1991. Design and analysis of experiments. 3d ed. John Wiley & Sons, Inc. 649 p.

Nelder, J.A. 1962. New kinds of systematic designs for spacing experiments. Biometrics. 18: 283-307.

Pacheco, A.C.; Tomé, M.; Delgado, J.; Silva, P.O.; Tomé, J. 1997. Pattern of water extraction, water availability and growth in young *E. globulus* planted with different spacing. In: Proceedings of the IUFRO Conference on silviculture and improvement of Eucalypts; 1997 August; Colombo, Embrapa. CNPF, vol. 3: 125-129.

Pereira, J.; Linder, S.; Araújo, M.C.; Pereira, H.; Ericsson, T.; Borralho, N.; Leal, L.C. 1989. Optimization of biomass production in Eucalyptus globulus plantations – a case study. In: Biomass production by fast growing trees. Dordrecht, The Netherlands: Kluwer Academic Publishers: 101-121.

Tomé, M. 1990. Modelação do crescimento em altura dominante em eucaliptais com recurso a análise multivariada e análise de regressão. In: Turkman M.; Carvalho, M., eds. Actas da 1ª Conferência em Estat'stica e Optimização; 1990. Lisboa, INIC and DEIO (Univ. Lisboa): 443-462.

Vanclay, J.K. 1994. Modelling forest growth and yield. Applications to mixed tropical forests. Wallingford, UK: CAB International. 312 p.

Westoby, M. 1984. The self-thining rule. Advances in Ecological Research. 14: 167-225.

The Effect of SO_2 Pollution on Pine Needle Structure

E.A. Zhitkova and L.L. Novitskaya

Abstract.—Fall and winter needles from pines growing near the Kostomuksha ore-dressing mill (KODM) were collected and studied by light microscopy. Fall needles showed symptoms of SO_2 influence and no specific seasonal changes in mesophyll. The injury rates of needle surface and mesophyll showed that pollutants penetrate into the needles through stomata and cuticle. Compared to fall needles winter needles exhibited a greater number of destroyed mesophyll cells and heavy cuticle damage. The effect of the KODM pollutants is thought to reduce the tolerance of mesophyll to low temperatures. It is obvious that pine needles near the KODM suffer both from acid rain and SO_2.

FALL NEEDLES

0.5 - 2 Kilometers From Mill

First-Year Needles

High vesiculation rate is characteristic of mesophyll cells. Tannin appears as a thick ribbon, in a granular form, or as a droplike substance. Some cells seem to be "empty" because the vacuole outlined with tannin fills in the whole cell. It is impossible to distinguish cytoplasm between tonoplast and plasmalemma. The study of serial sections shows that the next stage in these "empty" cells' structure can be their full disintegration and cell wall destruction. This would increase the intracellular space.

Chloroplasts of the living cells are big and rounded, and sometimes concave. Their dark coloring indicates the presence of plastoglobuli. Occasionally, starch grains can be detected in plastids.

It should be noted that "empty" and semidestroyed cells are situated in inner mesophyll layers closer to endoderma or resin canals. Both the abaxial and adaxial needle sides demonstrate destroyed cells.

Parenchyma cells of vascular bundles show tannin and lipid accumulation. Needle cuticle and surface tissues are strongly injured. Sometimes the epidermis splits off from the hypodermis.

Second-Year Needles

The difference between the first- and second-year needles is that the latter have more "empty" and semidestroyed mesophyll cells and larger intracellular spaces. In some cells, tannin occurs as large lumps, which are not seen in first-year needles.

25 Kilometers From Mill

First-Year Needles

In inner mesophyll layers, the needle cells have more varied conditions. Thus, the cells with granular tannin in their vacuoles are adjacent to cells containing granular and ribbonlike tannin in their vacuoles. Chloroplasts are occasionally small and dark, or in adjacent cells they can be larger, blurred, and of pale pink color. In some sections, large intracellular spaces are located close to endoderma and resin canals. The total necrosis of needle angles can often be observed: epidermis and hypoderma are destroyed, and only remnants of mesophyll cell walls can be distinguished.

Second-Year Needles

The needles seem to be heavily injured. Only some cells have the average rate of damage. The protoplast and walls of mesophyll cells are being destroyed. In some needle sections, the adaxial side shows total necrosis; on the abaxial side of the needle, half of the mesophyll cells are at different stages of destruction. Tannin lumps can be found in some cells.

WINTER NEEDLES

Winter needles show a greater rate of injury. In general, the needle sections were found to have more destroyed mesophyll cells as compared to those of fall needles.

Graduate student, Forest Institute, Russian Academy of Science, Petrzavodsk, Karelia, Russia; and Professor, Head of the Laboratory for Cytology and Physiology of Woody Plants, Forest Research Institute, Russian Academy of Science, respectively.

Chloroplasts are very large; this is likely due to their strong swelling. Needle surface also seems to be greatly destroyed. Ruptures run through the epidermal and hypodermal layers towards the mesophyll. Such needles can hardly survive winter frosts.

CONCLUSIONS

Cytological analysis revealed the disturbance of normal seasonal changes in the mesophyll of pine needles in the vicinity of the Kostomuksha ore-dressing mill (KODM). Healthy cells were found to have the normal structure characteristic of the fall-winter season with large tannin granules and light cytoplasm.

The first stage of damage is characterized by darkened cytoplasm, large tannin granules, along with a thin ribbon along the margin of the central vacuole. At the second stage of damage, the cells contain tannin in the form of a thick ribbon and very large scattered granules, or large lumps (in the second-year needles). "Empty" cells show the third stage of damage. Tannin is seen as a thick ribbon or often completely disappears. Cytoplasm also disappears or is difficult to detect. This stage appears to be final and is followed by complete cell destruction.

During winter dormancy, mesophyll cell structure is characterized by the growing amount and condensation of tannin to large granules (Anttonen and Karenlampi 1996; Palomaki and Ratio 1995; Soikkeli 1978, 1980). The ribbonlike state of tannin goes along with cellular membrane disturbances and is a sign of inadequate hardening. An increased amount of tannin is thought to influence the frost resistance of cells: tannins may significantly affect the vacuole water potential by changing its osmotic potential. Experiments with the use of different molarity of fixative buffer on pine needles showed the dependence of tannin structure on cellular osmotic potential (Soikkeli 1980).

Seasonal changes in tannin condition during fall-winter and spring-summer are thought to be connected with fluctuations in osmotic pressure in the needles in the summer and winter (Huttunen *et al.* 1981). Osmotic potential is determined by the tonoplast condition; active transport of ions and molecules into the vacuole is taken as its function. Changes in the tannin structure can indicate the structural and functional alterations in tonoplast.

Sulphur dioxide affects the structure of cellular membranes and their functional activity (Malhotra and Hocking 1976). SO_2 results in the condensation of tannin to large granules as well as ribbon on the vacuole margin (Soikkeli and Tuovinen 1979, Sutinen and Koivisto 1992). Air pollution with SO_2 around the KODM is thought to cause the abnormal tannin accumulation in pine needle mesophyll cells by altering tonoplast properties, which is followed by changes in vacuole osmotic potential.

Chloroplasts in injured mesophyll cells are very large, light in color, and blurred; in other cells, they are small and dark. Obviously, there is swelling of plastid membranes and accumulation of light plastoglobuli in stroma of chloroplasts in some cells, which is typical for needles affected by sulphur dioxide (Soikkeli and Tuovinen 1979, Sutinen and Koivisto 1992). In these cells, large plastids are situated along cell walls, as is their summer arrangement. However, grouping of plastids and their translocation into the cell corners is typical for intact autumn-winter needles (Anttonen and Karenlampi 1996; Palomaki and Ratio 1995; Soikkeli 1978, 1980).

Structural analysis of the winter needles revealed increased damage as compared to the fall needles. Our results showed that the impact of the KODM pollutants on pines reduces the tolerance of needle tissues to low temperatures by winter hardening disturbance.

Heavy damage of the needle cuticle and disturbance rates of surface and internal needle tissues show that pollutants penetrate into the needles through stomata and cuticles. Tannin and lipid deposits in parenchyma cells of vascular bundle indicate that vascular tissues participate in the removal of excessive pollutants from needles. Pine needles collected near the KODM are thought to suffer from SO_2 impact along with acid rain and natural stress factors such as winter frosts.

ACKNOWLEDGMENT

The author is grateful to: Valery A. Isidorov, Department of Analytical Chemistry, and Vsevolod V. Polevoi, Department of Plant Physiology, St. Peterburg University.

LITERATURE CITED

Anttonen, S.; Karenlampi, L. 1996. Slightly elevated ozone exposure causes cell structural changes in needles and roots of Scots pine. Trees. 10: 207-217.

Huttunen, S.; Karenlampi, L.; Kolari, K. 1981. Changes in osmotic potential and some related physiological variables in needles of polluted Norway spruce (*Picea abies*). Annals of Botany Fennici. 18(1): 63-71.

Malhotra, S.S.; Hocking, D. 1976. Biochemical and cytological effects of sulphur dioxide on plant metabolism. New Phytology. 76: 227-237.

Palomaki, V.; Ratio, H. 1995. Chemical composition and ultrastructural changes in Scots pine needles in a forest decline area in southwestern Finland. Trees. 9: 311-317.

Soikkeli, S. 1978. Seasonal changes in mesophyll ultrastructure of needles of Norway spruce (*Picea abies*). Canadian Journal of Botany. 56(16): 1932-1940.

Soikkeli, S. 1980. Ultrastructure of mesophyll in Scots pine and Norway spruce: seasonal variation and molarity of fixative buffer. Protoplasma. 103: 241-252.

Soikkeli, S.; Tuovinen, T. 1979. Damage on mesophyll ultrastructure of needles of Norway spruce in two industrial environments in central Finland. Annals of Botany Fennici. 16(1): 50-64.

Sutinen, S.; Koivisto, L. 1992. Cell injuries in the needles of Scots pine (*Pinus sylvestris*) in Finnish Lapland. A light and electron microscopic approach. Proceedings, symposium on the state of the Environment and Environmental Fennoscandia and the Kola Peninsula; 1992 October 6-8; In: Arctic Center Publications. 4: 232-234.

The U.S. Department of Agriculture (USDA) prohibits discrimination in all its programs and activities on the basis of race, color, national origin, gender, religion, age, disability, political beliefs, sexual orientation, and marital or family status. (Not all prohibited bases apply to all programs.) Persons with disabilities who require alternative means for communication of program information (braille, large print, audiotape, etc.) should contact USDA's TARGET Center at (202) 720-2600 (voice and TDD).

To file a complaint of discrimination, write USDA, Director, Office of Civil Rights, Room 326-W, Whitten Building, 14th and Independence Avenue, SW, Washington, DC 20250-9410, or call 202-720-5964 (voice or TDD). USDA is an equal opportunity provider and employer

☆ U.S. GOVERNMENT PRINTING OFFICE: 2000–557-283

Printed on recyclable paper.

Hansen, M.; Burk, T., eds.
2000. Integrated tools for natural resources inventories in the 21st century, proceedings of the IUFRO conference; 1998 August 16-20; Boise, ID. Gen. Tech. Rep. NC-212. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station. 743 p.

Includes 96 papers presented at the conference Integrated Tools for Natural Resources Inventories in the 21st Century, August 16-20, 1998, in Boise, Idaho, USA. This conference drew several hundred forest inventory and related professionals from multiple organizational levels and over 30 foreign countries. Topics covered include those related to natural resource inventory design, analysis and management applications; measurement consistency issues; data management, GIS and remote sensing applications; forest growth model interfaces; and special purpose inventories and applications.

KEY WORDS: Integrated inventories, inventory databases, remote sensing, urban forestry, volume, biomass, height, modeling, spatial information, growth, survival, mortality, annual inventories.

Our job at the North Central Forest Experiment Station is discovering and creating new knowledge and technology in the field of natural resources and conveying this information to the people who can use it. As a new generation of forests emerges in our region, managers are confronted with two unique challenges: (1) Dealing with the great diversity in composition, quality, and ownership of the forests, and (2) Reconciling the conflicting demands of the people who use them. Helping the forest manager meet these challenges while protecting the environment is what research at North Central is all about.

NORTH CENTRAL
FOREST
EXPERIMENT STATION